Prospects for China's Next-Generation Clean & Low-Carbon Technologies

Report / December 2023

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RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and in Beijing, People's Republic of China.

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Table of Contents

Introduction 6

1. Carbon Neutrality "Power Source":

China's Power Battery Prospects 9

Life of the Power Battery: From Saving Energy to Zero Carbon 10

From Technology to Cost: Key Features and Development Trends of Power Batteries 12

New Energy Vehicle: A Key Application of the Power Battery 16

Looking Forward: Power Batteries in the Future 19

2. Energy Saving "Cornerstone" for Buildings:

Heat Pumps Now and in the Future 20

Heat Pump: The Most Promising Low-Carbon Building Heating Technology 21

Potential for Heat Pump Energy Savings and Decarbonization 21

From Now to the Future: Mastering the Heat Pump Market 24

Tap the Potential: Heating Demand in Regional Markets 27

3. Zero-Carbon Steel "Core":

Iron Ore Electrolysis Technology Outlook 31

Iron Ore Electrolysis: Most Promising Technology for Zero-Carbon Steel 32

Focus on Two Technical Routes of Iron Ore Electrolysis Technology 32

Development Prospect of Iron Ore Electrolysis Technology in China 37

4. Zero-Carbon “Reaction”:

Examining Flow Battery Energy Storage 40

Booming Energy Storage Market and Strong Growth of New Energy Storage 41

Flow Battery Is Safe and Durable, with Unique Comparative Advantages 43

Flow Battery Technology Has Diverse Branches with VRFB Taking the Lead 46

Cost Reduction and Efficiency Improvement Imperative, and Market Guidance Indispensable 48

Introduction

The United Nations Climate Change Conference (COP27) officially concluded on November 20, 2022. The most representative outcome of the conference was the agreement on a new loss and damage fund, which not only creates a new platform for further cooperation among developed and developing countries in dealing with climate risks but also highlights once again the importance of technology and investment in addressing climate change and achieving the zero-carbon transition.

As more countries and regions announce carbon neutrality goals, their focus has turned to the transition path and potential actions. Given that the carbon neutrality goal poses great challenges to the energy system, the world should pay more attention to clean- and low-carbon technologies to fully unleash the potential of the zero-carbon transition and effectively achieve carbon neutrality while creating new room for market growth.

According to the *World Energy Investment 2022* report, released by the International Energy Agency (IEA), the annual average global growth rate in clean-energy investment has increased to 12% since 2020 under government financial and sustainable investment support, well above the 2% of 2015–20. However, because of the impact of the COVID-19 pandemic, current investment growth has led to rising supply chain costs and price surges in labor and materials, including cement, steel, and key minerals. To achieve the zero-carbon transition, future investments in clean energy will need to increase even faster.

With the guidance of the carbon peak and carbon neutrality goals and robust support from industry and markets, China has played a leading role globally in developing clean-energy technologies. In 2021, China invested RMB 380 billion in clean-energy development, more than any other country in the world. Especially in renewable energy, grid upgrades, and new energy vehicles, policy support and rapid technological advances have enabled China to become self-sufficient in new energy and decarbonization areas and to lead the global energy transition through large-scale exports.

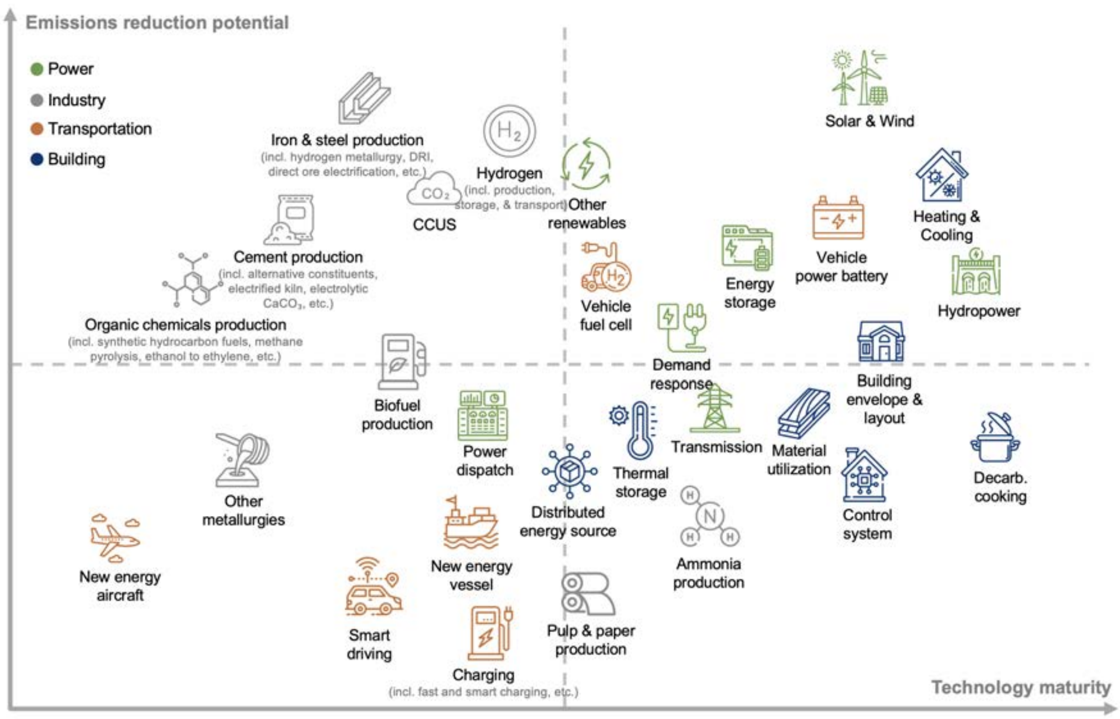
On the other hand, the scale and level of development of clean-energy technologies is still far from what is needed for the zero-carbon transition. Research institutes estimate that China's carbon-neutral goal will require at least RMB 100 trillion in total investment, most of which should be used in clean energy and breakthrough emissions-reduction technologies. Although China has made significant achievements in renewable power generation and new energy vehicles in the past 5 to 10 years, continuous development of existing transition efforts and the commercialization and scale of innovative technologies such as energy storage, hydrogen, carbon capture and storage, voltage source converter high voltage direct current (VSC-HVDC), and vehicle-to-grid (V2G) still require long-term investment and incubation.

RMI has conducted a series of *China Low-Carbon and Clean Technologies Outlook* studies, aimed at systematically reviewing the clean-energy and low-carbon technologies needed in China's future zero-carbon transition. The goal is to provide stakeholders — including policymakers, businesses, and investors — with suggestions on the direction and optimization of technology development, including:

- more clearly identifying the roles of clean-energy and low-carbon technologies in the carbon-neutral transition
- determining application scenarios, core components, leading providers, cost economies, and a time line of commercialization of different technologies
- discovering development models and needed policies and investments

Starting with a literature review, RMI identified about 300 common clean-energy and low-carbon technologies around the world. Fifty of the more promising technologies in the power, transportation, industry, and building sectors were selected based on actual market demand in China, and their maturity and emissions-reduction potential were assessed comprehensively (visualized in Exhibit 1).

Exhibit 1: **Maturity-Emissions-Reduction-Potential Matrix of Clean-Energy and Low-Carbon Technologies in China**



RMI Graphic. Source: Literature review, RMI analysis

RMI will continue to explore in depth the 50 technologies, analyzing specific features, application scenarios, cost and economic dynamics, time lines of commercialization, and major stakeholders, and suggesting promotional policies and investments for each of the technologies through a series of insight briefs. This systematic and targeted analysis will clarify technology development trends for industries, supply references on application scenarios and time lines for businesses, illustrate supporting policy directions to accelerate technological breakthroughs for policymakers, and present viewpoints on further investment targets and scale to support financial institutions' decision-making.

This report contains the first four insight briefs of the *China Low-Carbon and Clean Technologies Outlook* series, including:

- Carbon Neutrality "Power Source": China's Power Battery Prospects
- Energy Saving "Cornerstone" for Buildings: Heat Pumps Now and in the Future
- Zero-Carbon Steel "Core": Iron Ore Electrolysis Outlook
- Zero-Carbon "Reaction": Examining Flow Battery Energy Storage

We will provide recommendations for accelerating the development and application of the four low-carbon technologies (power batteries, heat pumps, iron ore electrolysis, and flow battery energy storage). More insight briefs on further topics will be released soon.

1. Carbon Neutrality "Power Source": China's Power Battery Prospects

In the era of carbon neutrality, new energy vehicles will soon dominate the transportation market, elevating the importance of the power battery and making it the new "power source." As a result, questions about the power battery's future market growth, technical performance, cost, and especially how to advance the promotion and adoption of new energy vehicles, are increasing. In this first insight brief of the *China Low-Carbon and Clean Technologies Outlook* series, the research team answers the questions above and describes the future direction of power battery technology as well as the support it will need.

Regarding the status quo and prospects for application of power battery technology, our observations are as follows:

(1) China is the world's one of the most important power battery market. Incentivized by its carbon neutrality goals, China's power battery production and sales will continue to lead the world.

(2) In the past decade, lithium-ion batteries have made significant breakthroughs in energy density and cost, but there is still a lot of room for growth.

(3) Based on the trend of technological development, power batteries can support the electrification of more than 90% of vehicles in China's road transport industry by 2050; the remaining 10% are mainly long-distance passenger vehicles and mid- and heavy-duty trucks, which will rely on further breakthroughs in battery technology or adoption of other new energy technologies and market models.

(4) Based on the current development rate of battery technology, as well as infrastructure and market trends, traditional liquid lithium-ion batteries will be able to meet the electrification needs of urban commuting private cars, buses, ride-hailing cars, and taxis around 2025, when the cost of ownership of these EVs will be lower than that of internal combustion engine (ICE) vehicles.

(5) New battery technologies such as sodium-ion batteries and solid-state batteries will play an important role in accelerating vehicle electrification. After 2030, liquid lithium-ion batteries, solid-state batteries, and sodium-ion batteries will coexist in the market as critical technology options for electrification.

(6) In the long run, the power battery industry has large growth potential. Proactive investment will accelerate the incubation and cultivation of new technologies and could lead overall development of the battery and new energy–vehicle industry.

(7) The power battery industry chain is a huge system. Its long-term development not only requires multidimensional policy support on multiple aspects, but also needs effective interconnections between upstream and downstream elements of the industry chain and the establishment of a circular economy and whole life–cycle system as soon as possible, to achieve complete zero

emissions in its own production and end-of-life management processes.

The following sections of the report describe the logic and analysis behind the above opinions. We look forward to discussions on any content or topic of interest.

Life of the Power Battery: From Saving Energy to Zero Carbon

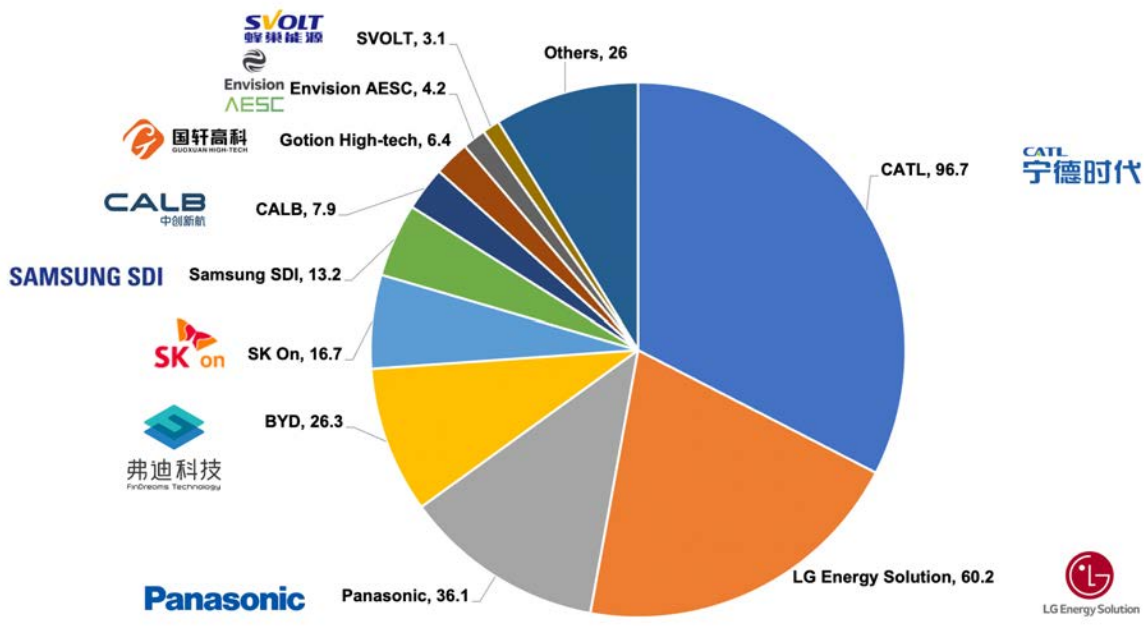
"Power battery" refers to the battery used in the mobility sector to provide power in EVs; it has been seen as an emerging type of battery in recent years. In fact, EVs and power batteries date back to the 19th century, though their popularity dwindled because of constraints on battery performance and infrastructure, and the rapid development of ICE vehicles. An energy crisis in the 1980s sparked new developments of EVs, and industry pioneers such as Tesla, Panasonic, and CATL further accelerated the explosive growth of the power battery industry in the 21st century.

In the context of China's carbon peaking and neutrality goals, applications for the power battery are no longer limited to EVs and transportation electrification. Chemical energy storage based on power battery technology is well positioned to become an important component of the new power system, laying a solid foundation for the stable and safe integration of clean energy into the grid. Therefore, lithium battery–focused power battery technology has become one of the core technologies for China to achieve energy transition and the carbon peak and carbon neutrality goals.

China is currently the world's largest market for new energy vehicles. Having benefited from infrastructure planning, policy support, and a mature power battery industry chain, China accounted for more than 60% of global total new energy vehicle sales in 2021. Since 2015, several waves of vehicle electrification have taken place successively in different segments, including buses, taxis, light logistics vehicles, and private cars. Driven by China's carbon neutrality goal and increasing user demand, the penetration rate of EV sales exceeded 20% for the first time in November 2021.

The solid and robust industry-leading position of China's power battery industry has played an important role in supporting the explosive growth of EVs. In 2021, China produced 219.7 gigawatt hours (GWh) of lithium batteries (including domestic producers and factories of international producers in China), accounting for more than 80% of global production, while newly installed power batteries and energy storage batteries in China reached 154 GW and 1.87 GW, respectively, making China the leader in the world's power battery production and consumption. Six of the top 10 global power battery producers in terms of installed capacity in 2021 were Chinese companies, and most of the other international players in the list have set up production facilities in China (visualized in Exhibit 2).

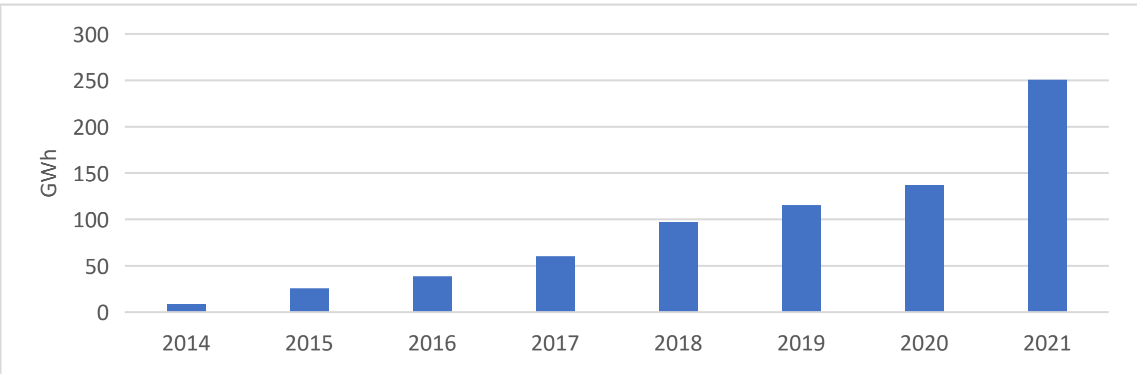
Exhibit 2: Global power battery installed capacity, by company (GWh)



RMI Graphic. Source: Literature review, RMI analysis

As the EV market is expected to expand at an accelerated pace in the next few years, along with massive adoption of energy storage batteries BloombergNEF predicts that global demand for power and storage batteries will reach 2.8 terawatt hours (TWh) by 2030, a tenfold increase from the 2021 level. However, even with the new energy–vehicle, and power battery industry booming around the world, the market share of China’s power batteries will remain above 50% by 2030, totaling about 1.5 TWh. Exhibit 3 shows the increasing trend of global annual new installed capacity of power batteries.

Exhibit 3: Global annual new installed capacity of power battery increases year by year



RMI Graphic. Source: Literature review, RMI analysis

From Technology to Cost: Key Features and Development Trends of Power Batteries

Exhibit 4: **Different power battery products and specifications**

Battery	Manufacturer	Chemical feedstock	Special process	Battery management and assembly	Performance features
4680-type	Tesla/ Panasonic	High-nickel ternary cathode + silicon-based anode	Tabless	Cell to Chassis	High energy intensity
Blade battery	BYD	Lithium iron phosphate cathode + graphite anode	Stack	Cell to Pack (CTP) blade design	High safety level

RMI Graphic. Source: Literature review, RMI analysis

Among all components and manufacturing processes, the most important factor affecting battery performance is the choice of chemical materials (Exhibit 4). In terms of cathode materials, two mainstream categories of materials have been widely adopted after years of selection and elimination: the lithium iron phosphate cathode and the ternary cathode (ternary refers to the oxides of nickel, manganese, and cobalt or nickel, cobalt, and aluminum mixed in different proportions). Advantages of the lithium iron phosphate cathode include low cost, long life, and high safety, whereas the advantages of the ternary cathode are high energy density and good performance under low temperatures. These two types complement each other and account for almost the entire EV market. In terms of anode materials, most battery manufacturers choose graphite-based materials, although some leading manufacturers have begun to move toward a silicon-based anode, which has higher capacity but also a more difficult technology.

Exhibit 5: **Typical cathode and anode materials**

Typical cathode materials	Lithium iron phosphate	**Typical anode materials**	Graphite
	Nickel manganese cobalt		Silicon/graphite composite
	Nickel cobalt aluminum		Silicon based anode
	....		....

RMI Graphic. Source: Literature review, RMI analysis

Energy density and cost are the most critical factors used to evaluate performance of a power battery.[i] Energy density determines the mileage range of new energy vehicles, which is the key to determining their ability to replace ICE vehicles in certain applications, whereas cost determines the price of new energy vehicles and affects their attractiveness and adoption. Combining these two factors directly reflects the cost-effectiveness of new energy vehicles and will critically influence the progress of electrification of the transportation industry.

Energy density

The energy density of a power battery is determined by multiple factors, including cathode and anode materials, the manufacturing process, and interaction patterns among the components of the internal system. The development of power battery energy density in the past decade can be divided roughly into two stages. From 2010 to 2018, the belief that "mileage range means all" prevailed, driving the sector to treat energy density development as a game changer. At that stage, lithium iron phosphate and ternary lithium batteries stood out from other chemical materials, such as lithium manganate, lithium titanate, and even nickel metal hydride. Lithium iron phosphate and ternary lithium batteries became the dominant types and pushed average energy density from about 100 watt hours per kilogram (Wh/kg) to about 170 Wh/kg (lithium iron phosphate) and 250 Wh/kg (ternary).[ii]

After 2018, increasing metal prices and difficulties with energy density breakthroughs, as well as a growing number of accidents, led to more emphasis on stability, safety, affordability, and longevity. The growth of battery energy density slowed down significantly in this stage, with the average power density of single cells and battery packs being about 180 Wh/kg and 144 Wh/kg, respectively, in 2021 (Exhibit 5). While striving to improve and explore the potential of existing power battery technologies, leading manufacturers also began to focus on the research and development of the next generation of battery technology with the purpose of further breaking through the bottleneck of energy density.

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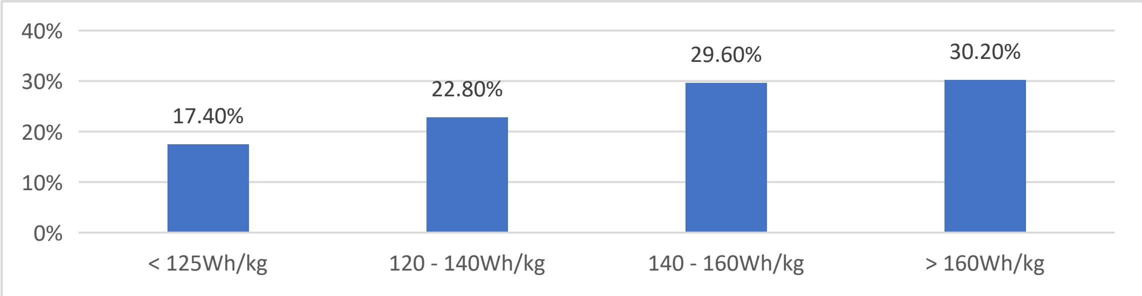
[i] Energy density, or the amount of electrical energy per unit weight, is the most common measure of battery performance. The higher the battery energy density, the more batteries a vehicle can carry, hence the farther the vehicle can drive and the less dependent it is on the charging network.

[ii] 2013 Research on the development and promotion policy on the automotive power battery industry, China Automotive Technology and Research Center

Exhibit 6: **China's EV battery pack energy density distribution as of December 2021**



RMI Graphic. Source: Literature review, RMI analysis

However, to achieve the goal of full electrification and zero-carbon transition in the transportation sector, power batteries' energy density needs to increase further to meet various use scenarios. Since 2017, China has begun to incorporate requirements related to the energy density threshold of power batteries in new energy–vehicle purchasing subsidy qualifications. At the end of 2021, the Ministry of Industry and Information Technology (MIIT) revised its "Standard Conditions for Lithium-Ion Battery Industry," further raising the minimum energy density requirements for new battery production. Specifically, the required energy density of ternary lithium batteries was increased to ≥210 Wh/kg for single cells and ≥150 Wh/kg for battery packs, and the required energy density of other lithium batteries was increased to ≥160 Wh/kg for single cells and ≥115 Wh/kg for battery packs.

MIIT released the *Energy Conservation and New Energy Vehicle Technology Roadmap 2.0* in 2020, which predicted that by 2030, the energy density of regular batteries would reach 250 Wh/kg for single cells and higher than 400 Wh/kg for high-end models, a boost of more than 40% from the 2020 level, further increasing the competitiveness of new energy vehicles in high-end passenger cars and light- and medium-duty logistics vehicles (Exhibit 6).

Exhibit 7: **Forecast for the performance and cost of lithium-ion batteries**

	Current average	2030 forecast
Price of single cell	0.65 Yuan/Wh	0.4 Yuan/Wh
Price of battery pack	0.87 Yuan/Wh	0.54 Yuan/Wh
Energy density of single cell	180Wh/kg	> 250Wh/kg
Energy density of battery pack	144Wh/kg	> 210Wh/kg

RMI Graphic. Source: Literature review, RMI analysis

Current battery technology allows manufacturers to improve the energy density of batteries by upgrading cathode and anode materials and cell designs. However, given the chemical characteristics of battery materials, it is difficult to raise the energy density of a single unit of the traditional liquid-electrolyte lithium-ion battery above 350 Wh/kg.

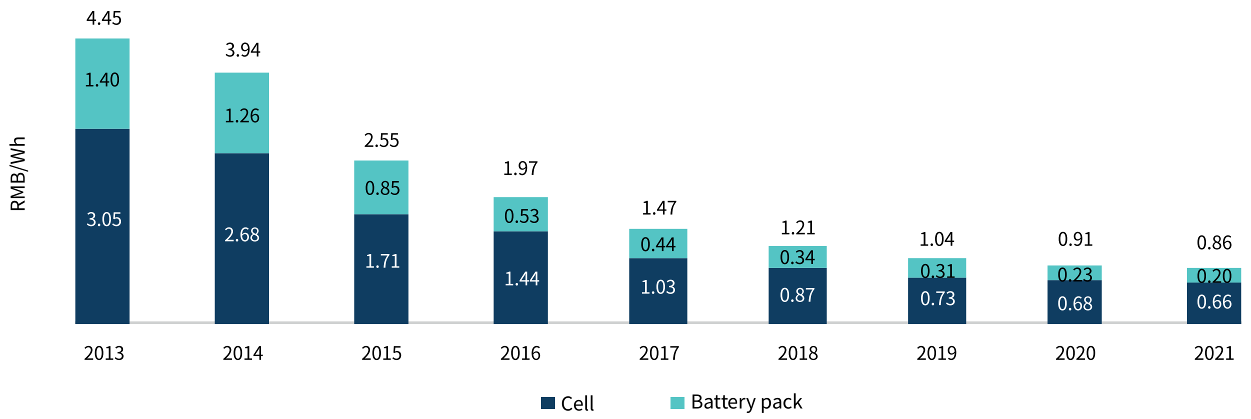
Therefore, to achieve a breakthrough in the mileage range performance of new energy vehicles, power battery manufacturers have begun to direct their R&D efforts toward innovative new battery technologies. Solid-state battery technology is generally considered to be more promising within the industry. It uses a solid-state electrolyte rather than a liquid organic electrolyte and membrane, and has better performance in terms of mechanical strength, safety, and energy density. The maximum theoretical energy density of a solid-state battery is 700 Wh/kg, twice that of a current lithium-ion battery.

Cost

The power battery and its system are usually the most expensive components of a new energy vehicle (about 40%, primarily from materials and R&D investment). As the new energy–vehicle market has grown, R&D costs have been fully amortized, and the total cost has fallen rapidly. In 2010, the average price of a single cell and a battery pack was about RMB 5/Wh and RMB 7/Wh, respectively, for lithium-ion batteries, whereas in 2020, the average prices were down by nearly 90% to reach about RMB 0.65/Wh for a single cell and RMB 0.87/Wh for a battery pack.

Nevertheless, there is still a gap between the current price level of power batteries and the level required for new energy vehicles to reach cost parity with ICE vehicles (meaning the total cost of buying and using an EV is equal to that of an ICE vehicle). For private vehicles, the price of a power battery pack needs to decrease to no more than RMB 0.65/Wh to achieve cost parity between EVs and ICE vehicles of the same specifications. New energy vehicles have disadvantages in terms of range and charging convenience, and commercial vehicles (such as logistics vehicles, especially long-haul heavy-duty trucks) are even more sensitive to cost and require greater cost decreases to fulfill electrification needs (battery price in cases of energy storage and new energy vehicles can be seen in Exhibit 8).

Exhibit 8: **Battery price calculated by volume-weighted average in application cases of energy storage and new energy vehicles**



RMI Graphic. Source: Literature review, RMI analysis

It is expected that the lithium-ion battery price decline trend will slow down in the next few years. As the main driving force for cost reduction in the past decade, the scaling effect has faded and the future cost reduction of lithium-ion batteries will rely mainly on technological innovation in cathode materials, production processes, and cell designs. Moreover, supply and demand balance, geopolitics, and resource distribution have led to increases in the prices of battery raw materials since 2021. The prices of cobalt, nickel, and lithium went up quite a lot, leading to a rise in battery prices in 2022. Although metal prices probably won't continue to rise in the long term, they are likely to remain well above the 2020 level, putting more cost pressure on battery producers.

In addition to exploring the potential for cost reduction in lithium-ion batteries, some manufacturers are also working on the next generation of low-cost batteries, such as the much-touted sodium-ion battery, which replaces the lithium in lithium-ion batteries with sodium without changing the basic working mechanism. Although the energy density is slightly lower, its cost will be more advantageous because sodium metal resources are abundant. It is expected that the cost of materials for sodium-ion batteries will be about 30% lower than that for lithium-ion batteries once the industry matures.

New Energy Vehicle: A Key Application of the Power Battery

The adoption and use of new energy vehicles will determine the development direction of and prospects for power batteries. And, conversely, advancements in power battery technology will directly affect the performance and market acceptance of new energy vehicles. Different types of new energy vehicles have different requirements for the performance and cost of power batteries. For example, it is less difficult to achieve electrification of urban-commuting private vehicles as they have relatively low mileage requirements, though they are sensitive to cost. On the other hand, electrification of heavy-duty long-haul trucks requires more advanced power battery technology in terms of energy density and cost to encourage their daily usage.

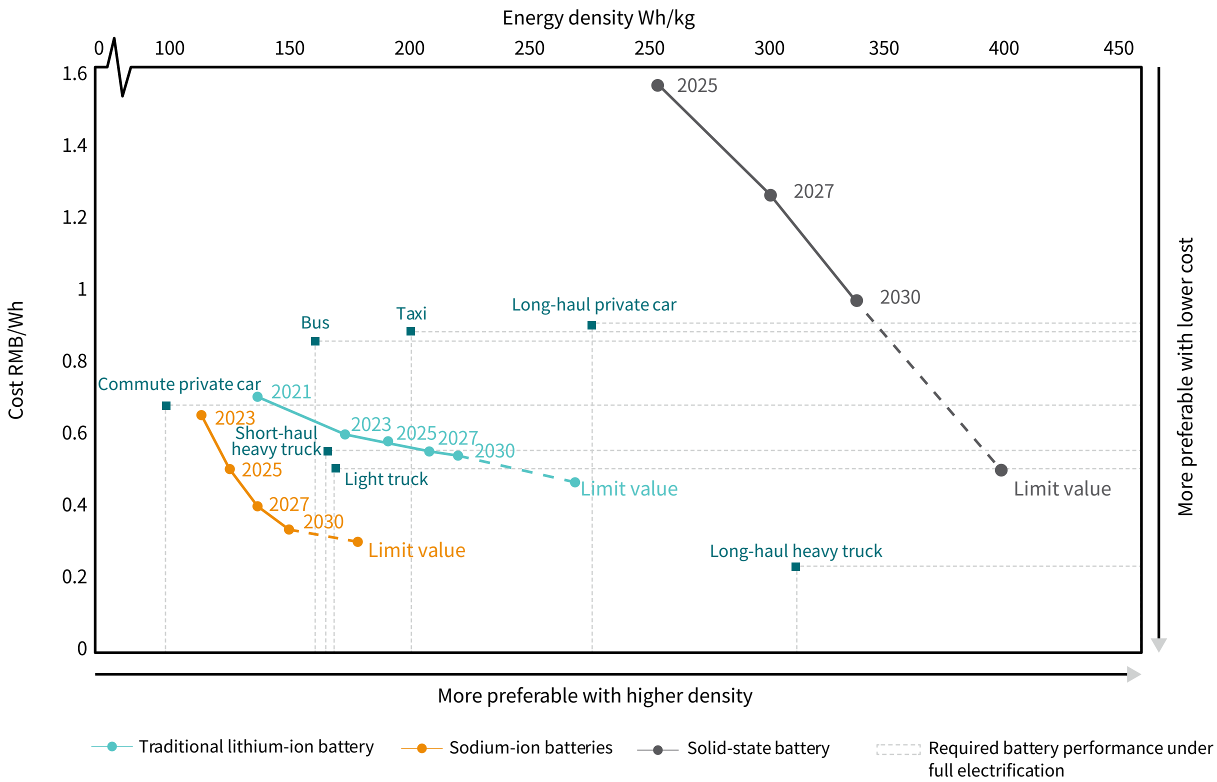
As a result, the development direction and prospect of power battery technology will not only be affected by raw materials and technology advances, but will also be closely related to its market positioning and applications. Therefore, in addition to analyzing the performance and cost trends of different power battery technology routes, it is important to systematically clarify the technical directions and development trends of power batteries by identifying the application cases of power batteries with new energy vehicles, as well as the electrification needs of different vehicle models and their use scenarios.

To clearly demonstrate the potential of future uses of power batteries, and the time frame and status that power batteries will need to achieve basic performance requirements to electrify different types of vehicles, we calculated the total cost of ownership (the sum of purchase costs, fuel costs, and maintenance costs within a certain service life) of various new energy vehicles and ICE vehicle models, and also analyzed the changing dynamics of different energy densities and costs. At the same time, based on predictions of energy density and cost trends of power batteries, we identified the technical performance levels required for different use scenarios to achieve the goal of full electrification.[iii]

[iii]Battery technology is only one of the factors contributing to the electrification of vehicles. Other charging modes, such as battery swapping, can greatly reduce charging time and the demand for driving range of a single charge, also accelerating the promotion and application of new energy vehicles. This paper focuses on the analysis of the impact of power battery technology on the electrification process, so the analysis of other technical areas such as battery swapping is relatively limited.

In our simulations and calculations, we assumed that the total cost of ownership of new energy vehicles is lower than that of ICE vehicles and that there is no significant relationship between energy density and cost, meaning both factors need to satisfy their own targets. The analysis results are shown in Exhibit 8. Among all vehicle types, urban commuting–passenger cars (mainly commuting private cars, taxis, and ride-hailing cars) with relatively short daily driving mileage will be the most common use scenario for lithium-ion batteries as they have fewer requirements for battery energy density and costs. At the same time, sodium-ion batteries may occupy a specific market share in the medium to long term because of the high potential for cost reduction. Given that cost-effectiveness is still the most important factor affecting the promotion and adoption of new energy vehicles in this use case, the core breakthrough, in this case, is to further expand energy density and reduce cost through technology R&D and to scale expansion on the premise of safety.

Exhibit 9: **Development trends of power battery performance and analysis on required power battery performance of different vehicle types**



RMI Graphic. Source: Literature review, RMI analysis

Urban buses are similar to intracity commuting vehicles, but their use scenario is more fixed. Electric buses have seen the fastest growth in the past few years, but this is largely the result of government incentives and heavy subsidies, and the cost of electric buses remains higher than that of ICE vehicles. The advantage of buses is that the driving route, timetable, and frequency are clearly planned with low uncertainty, making it easier to arrange charging times and locations and reduce required battery capacity. Given the relatively high demand for battery capacity by buses, the next-generation lithium iron phosphate battery will still be the primary option for bus electrification.

Light-duty trucks and short-haul heavy-duty trucks are used in similar cases, and both require higher power battery capacity because of their greater power consumption. Short-haul heavy-duty trucks are mainly responsible for freight transport in such cases as ports, park logistics, and short-haul transfers. Despite heavy loads and high power consumption, driving distances are short, meaning battery energy density doesn't need to be high, but the requirements for battery cost and size are harsh. Therefore, future lithium-ion batteries, assuming technology breakthroughs, could be ideal for electrification of these vehicles.

Long-distance private cars and heavy-duty trucks are the most difficult use cases to electrify. It is impossible for new energy vehicles to achieve cost-effectiveness in both cases with current battery technology. Continuous R&D and exploration will possibly drive solid-state batteries to reach the required energy density and cost to electrify private cars with long-distance travel needs around 2030 but still cannot completely solve the problem of long-haul heavy-duty trucks, where hydrogen fuel cells may be needed to supplement and support.

In this sense, power batteries' future utilization scenarios will focus on urban passenger vehicles and commercial vehicles for short-distance transportation, including buses, light logistics vehicles, heavy-duty trucks at ports, and urban or regional heavy-duty trucks. Long-distance private cars may become synonymous with high-end EVs in the future because of the difficulties in electrification and cost reduction. Long-haul heavy-duty trucks are the most difficult to electrify solely by advances in battery technology.

From the perspective of battery technology classification, solid-state batteries will mainly be used in high-end passenger cars, mid- and long-haul heavy-duty trucks, and some light logistics vehicles; despite having lower energy density compared with lithium-ion batteries, sodium-ion batteries will have a promising future in commuting use cases because their cost will decline rapidly. Liquid-electrolyte, lithium-ion batteries will cover other passenger and commercial vehicles.

Looking Forward: Power Batteries in the Future

The future development direction of power batteries is clear: to further increase energy density, reduce cost, and actively explore the development of new battery technologies, such as sodium-ion batteries and solid-state batteries. Due to their large market base and relatively stable performance, liquid lithium-ion batteries will still be the backbone for the accelerated adoption of new energy vehicles in the short term. Therefore, the continuous development of the technological potential of lithium-ion batteries through 2030 will be the key to ensuring the gradual transition to comprehensive electrification of urban vehicles. Meanwhile, other new battery technologies will also be critical to achieving full electrification of long-haul, mid- and heavy-duty vehicles if the commercialization process is gradually accelerated.

In addition, optimizing the whole life-cycle management of the power battery will gradually rise in importance. On the one hand, because the production of power batteries depends so much on mining and importing metal raw materials, international geopolitics and fluctuations in the metal materials market have increased uncertainty in the power battery industry. In the short term, reliance on mining constrains power battery capacity expansion and exacerbates supply pressures and price volatility in the metals markets. In the long run, although metal mineral reserves are sufficient to support the development of new energy vehicles in the next few decades, the gradual depletion of resources will lead to rising mining costs and negative impacts on the power battery and new energy-vehicle markets.

On the other hand, recycling and treatment of used batteries are creating opportunities to alleviate problems such as the shortage of upstream raw materials while also increasing the risk of environmental pollution. Because of insufficiently clear industrial regulations for power battery recycling and treatment, waste batteries that have not been properly treated will consume a lot of energy in the process of scrapping and may cause environmental pollution. How to fully use metal materials in end-of-life power batteries, control the impact on the environment through clean recycling and reuse in the circular economy, and use the recycled resources in the production of new batteries to relieve pressure on metal material supplies and achieve zero emissions in the whole life cycle will be key to the long-term development of the power battery industry.

In conclusion, the power battery industry has favorable development prospects and is of great value and significance to China in achieving the goal of carbon neutrality. In the next 10 to 20 years, power batteries will continue to make rapid progress in terms of technical performance and become the key to supporting the large-scale promotion and adoption of new energy vehicles in China. However, the development of the power battery is still affected by raw materials, capital, and technology. To maximize the role of the power battery, it is necessary to establish a robust policy and market environment and improve its whole life-cycle industrial chain.

This includes not only the continuous promotion of the development of the new energy-vehicle market and constantly improving requirements for battery energy density, but also the clarification of the needs and development stages of different power battery technologies in various types and use cases of new energy vehicles and improving the deployment of charging infrastructure. Also key is the establishment of the battery life-cycle management system, clarifying the battery recycling responsibility, strengthening battery recycling, and breaking the information barrier among battery producing and assembly companies, users, and recycling companies to ensure that retired batteries can be traced, collected, and recycled.

2. Energy Saving "Cornerstone" for Buildings: Heat Pumps Now and in the Future

Buildings consume most of the energy required by people's daily production and life. In 2021, China's building sector emitted 2.13 billion tons of CO_2, about 20% of the country's total carbon emissions. Promoting clean-energy alternatives and energy efficiency are key levers to drive building decarbonization and achieve carbon neutrality. In China, about 60% of buildings' daily operational energy consumption comes from heating, cooling, and water boiling. As one of the most promising technologies for decarbonization of buildings, the heat pump can effectively reduce energy consumption and emissions from traditional heating and cooling approaches by electrification and efficiency improvement, and thus is one of the most important solutions for buildings' zero-carbon transition in the future.

Considering that the heat pump is already commercially available, this insight brief briefly analyzes the technical competitiveness, future development direction, and penetration potential of the heat pump in different regions of China with cost-effectiveness and utilization scenarios. We hope this brief will help readers understand the current state of heat pump technology in China as well as its future applications and promotion directions. Key takeaways of this research include:

(1) The heat pump is one of the best decarbonization solutions for the building sector. It is predicted that heat pumps will account for 60% of demand for space and water heating in buildings under the 2050 zero-carbon scenario. The heat pump could effectively use low-temperature renewable heat sources in the environment to replace traditional combustion of fossil fuels and has the potential for increasing carbon reduction as its efficiency improves and the grid further decarbonizes.

(2) Among all types of heat pump products, the air-source heat pump is dominant and holds more than 90% of the market share. Water and ground source heat pumps could have larger market shares in certain locations and circumstances if reasonable planning and regulatory guidance are provided. In addition, the absorption heat pump will play a critical role in using industrial and power-generation waste heat for residential heating.

(3) A detailed cost-effectiveness analysis shows that some heat pump products have been competitive with traditional heating products from a cost perspective. However, because of the high up-front cost and a lack of awareness, stronger policy incentives are needed for further promotion and larger-scale adoption.

(4) Different regions should choose suitable heat pump products according to local climate conditions. For example, absorption heat pumps are suitable to replace the traditional fossil-fuel central heating systems used in North China regions; commercial or individual distributed heat pumps are more suitable for North China regions without central heating systems and South China regions with hot summers and cold winters.

Heat Pump: The Most Promising Low-Carbon Building Heating Technology

The heat pump is already a hot topic in the field of building decarbonization because it has huge decarbonization potential in heating and water boiling by replacing traditional fossil-fuel combustion or direct electric heating. Heat naturally flows from the high-temperature side (heat source) to the low-temperature side (demand side). In traditional heating, fossil energy is burned to create a high-temperature heat source and then transfer the heat to the demand side, emitting large amounts of carbon in the process. In addition, fossil fuels are usually burned at very high temperatures (usually above 500°C), which is much higher than actually needed for heating and therefore results in waste. (For example, hot water used in floor heating systems is usually not higher than 60°C.)

In contrast, heat pump equipment can absorb heat from low-temperature heat sources (such as air, shallow geothermal, etc.) and release it to the demand side, where the temperature is relatively higher, by using the phase change characteristics of a refrigerant, therefore saving energy and mitigating emissions.[iv]

Compared with traditional heating approaches, a heat pump could realize energy savings and carbon reduction via two major routes. First, a heat pump is usually driven by electricity, which is and will be much cleaner than fossil fuel–based systems as renewable power increases and the grid gradually decarbonizes. Second, most of the heat provided by the heat pump comes from the natural environment, which not only improves heating efficiency but also enables effective use of the Earth's renewable heat energy.[v] As a result, the heat pump has been categorized as renewable energy technology in many provinces. In addition to meeting a building's heating needs, heat pumps can be switched from heating mode to cooling mode, providing low-carbon cooling for buildings in the summer.

Potential for Heat Pump Energy Savings and Decarbonization

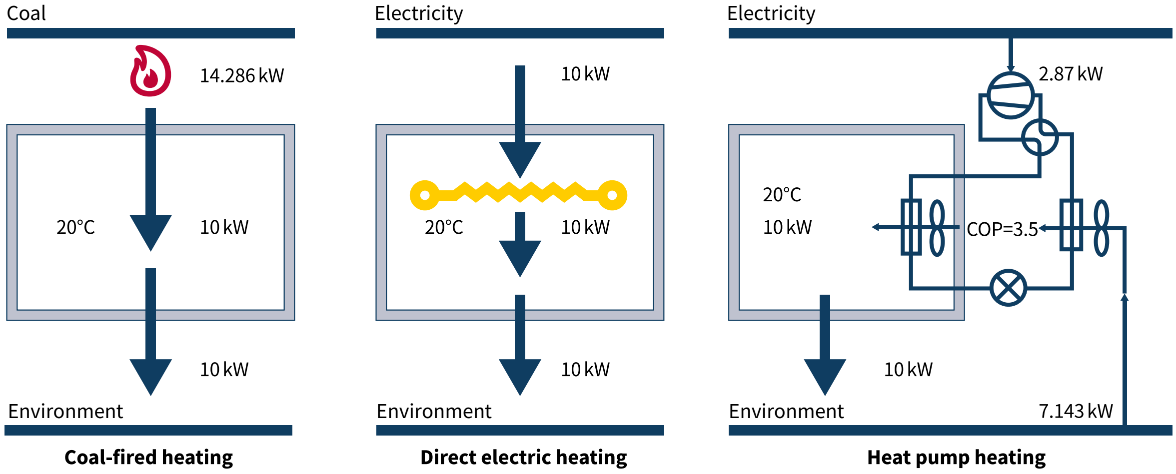
In terms of energy saving, heat pumps have obvious advantages over gas, coal, and ordinary electric direct-heating devices. Taking indoor heating as an example (see Exhibit 10), if 10 kilowatt hours (kWh) of heat is required to maintain a room at 20°C[vi], then about 14 kWh of chemical energy is needed from coal-fired heating (efficiency is about 70%) and about 10 kWh of electricity energy is needed from an electric resistance heater to directly heat the indoor air, but only about 3 kWh of electricity is needed from an electricity-driven heat pump, with the remaining energy of about 7 kWh grabbed from low-temperature thermal energy in the air (a heat pump's coefficient of performance [COP] is about 3.5[vii]).

[iv] The principle of the heat pump is that low-boiling-point "refrigerant" material evaporates in the evaporator while absorbing heat in the environment, and the resulting gas flows through the compressor to the condenser to liquefy while releasing heat, which heats the indoor space or water tank on the user side. Finally, the resulting liquid flows through the throttle valve for decompression, going back into the evaporator to repeat the cycle.

[v] As the thermal energy in the environment mainly comes from renewable heat sources such as the sun and geothermal, it is also included in the category of renewable energy.

[vi] Heat with kW as the unit in this paper refers to heat production, which is the sum of the heat provided by the air-conditioning system in heating mode or the water heating system, usually measured in W or kW.

Exhibit 10: **Illustration of different heating approaches**



RMI Graphic. Source: China Heat Pump Alliance, Heat Pump Supports Carbon Neutrality White Paper 2021

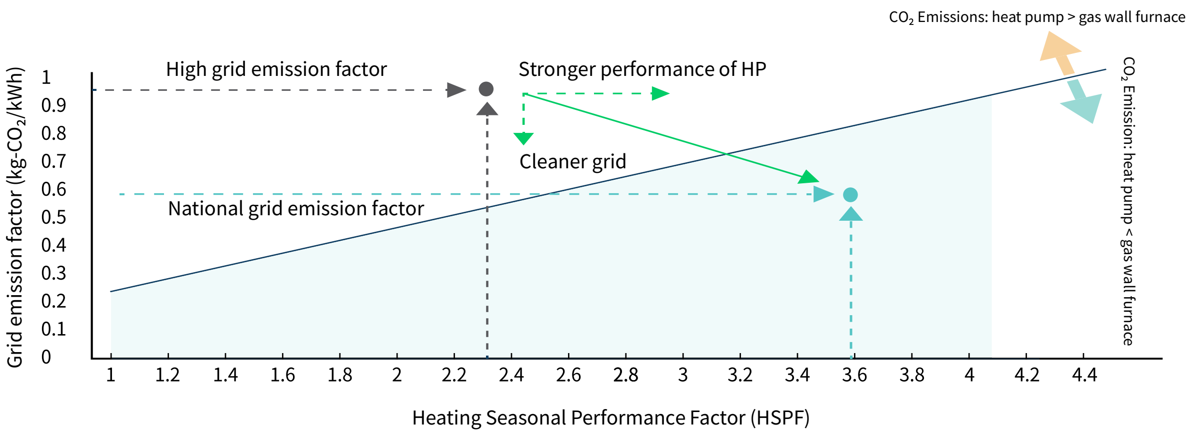
In terms of carbon emissions reduction, because a heat pump is usually driven by electricity, its carbon reduction potential mainly depends on its performance efficiency and grid emissions factors. A comparative analysis of heat pump and gas wall furnace carbon emissions concluded that if the intersection of the heating seasonal performance factor (HSPF) and the grid emissions factor is below the black line (blue shaded area), the heat pump has larger carbon reduction potential than a gas wall furnace, and vice versa (see Exhibit 11)[viii]. Assuming the HSPF of the heat pump is 3.5 and the national grid emissions factor is 0.5810 kgCO_2/kWh (published by the Ministry of Ecology and Environment in 2022), the heat pump will have a stronger decarbonization contribution than a gas wall furnace.

Further improvement of the heat pump COP and a lower grid emissions factor may enhance the carbon reduction potential of the heat pump. Therefore, considering the performance efficiency of the heat pump and grid emissions factors, in the short term, heat pumps could contribute more carbon reduction in renewable-rich regions such as the south Yangtze River region, with its hot summers and cold winters. In the long run, with the rapid adoption of renewable power nationwide, the grid emissions factor will be further reduced and the carbon reduction potential of heat pumps will continue to increase.

[vii]COP: Coefficient of performance is used to measure the efficiency of the heat pump, equal to the ratio of the heating/cooling capacity of the heat pump to the input power.

[viii]Part of the research data is from the paper "Energy Systems in Carbon Neutral Urban Buildings" by Weiding Long, Tongji University, scheduled to be published in the *Journal of HV&AC* in 2022.

Exhibit 11: **Illustration of different heating solutions**



RMI Graphic. Source: Literature research

Heat pump classification:

Usually, heat pumps are classified by the type of heat source, and they can be divided into air-source, ground-source, and water-source heat pumps, with outdoor air, underground soil, and surface or underground water, respectively, as heat sources. In addition, heat pumps can be classified by heat flow mechanisms, i.e. steam compression heat pumps, which rely on power consumption, and absorption heat pumps, which are driven directly by heat instead of electricity.

China's heat pump market is dominated by air-source heat pumps. According to ChinaIOL, sales of air-source heat pumps (including dual-generation systems of air-conditioning and floor heating) in China totaled about RMB 23.8 billion in 2021, accounting for about 96% of the heat pump market. Compared with water and ground source heat pumps, air source heat pumps are less restricted by local conditions and require a lower up-front investment. Air source heat pumps for buildings' space and water heating mostly fall into the product types shown in Exhibit 12.

Exhibit 12: **Comparison of air source heat pump products**

Function	Category	Region	Standard	Description	Representative businesses
Home heating	**Low-temperature, air- source heat pump**	All regions but mainly northern regions, especially high-altitude areas	GB/T 25127	Water heating (supplementary cooling) units that mainly replace traditional coal/gas boilers	Midea 美的; 海尔中央空调; GREE 格力; 中广 欧特斯; McQuay 麦克维尔; Carrier 开利空调; TRANE 特灵空调
	Normal-temperature, air-source heat pump	All regions but preferably southern regions	GB/T 18430	Water cooling (supplementary heating) units that replace both cooling air conditioners and electric gas heaters/underfloor heaters	
	Low temperature, heat pump hot air blower	Northern regions, especially extreme-cold regions	JB/T 13573	Rapid heating, strong frost resistance, low cost, but poor comfort	
Water heater	**Air-source water heater**	Unlimited Preferably Southern regions	GB/T 23137	Systems with high price and large tank volume that can replace traditional electric/gas water heater	海尔空气能; A.O.SMITH 史密斯

Source: Literature research

Compared with air-source heat pumps, water and ground-source heat pumps are more efficient, with low power consumption and less noise. Although installation has caused soil and water pollution, the development of water and ground source heat pumps has been attracting more attention. Lots of different brands share the market for water and ground source heat pump products because of the low barrier for market entry in the early development stage. However, market standardization and mainstream brand extension have led to more integration in recent years, with major domestic and foreign brands including Trane, York, Tsinghua Tongfang, and Shandong Keling.

Absorption heat pumps, which can effectively collect and use low-temperature heat sources, are widely used for industry and power sector waste-heat recovery. They have great potential to use intraregional and cross-regional waste-heat resources to provide heating for buildings. Absorption heat pumps are generally purchased by companies and organizations, with similar providers as compression heat pumps, including York and Tsinghua Tongfang.

From Now to the Future: Mastering the Heat Pump Market

Compared with traditional heating approaches, the heat pump has obvious advantages in energy consumption. It still has a lower adoption rate in the market because of low consumer awareness and the high cost in this early stage of market entry, but it is widely seen as one of the most promising clean heating solutions, driven by increased product cost competitiveness and decarbonizing trends in the building sector.

The IEA estimates that global heat pump stock comprised about 180 million units in 2020, which could satisfy about 7% of total heating demand. Under the zero-carbon scenario, heat pump stock should reach about 600 million by 2030 and about 1.8 billion units by 2050, with 30% in China. RMI predicts that by 2050, heat pumps could account for 60% of buildings space and water heating in China under the zero-carbon scenario.

Heat pump utilization scenarios vary as different regions have different heating demand and service levels. At present, major demand for heat pump heating products comes from new or renovated residential buildings, the “coal-to-electricity” transition, and real estate developers’ centralized purchasing.

According to the Heat Pump Committee of the China Energy Conservation Association, taking the air source heat pump water-based heater as an example: consumers’ self-purchases account for about 70% of total sales, mainly from areas with hot summers and cold winters in the south and a small part of the northern regions, with products mainly sold by retail dealers; government oriented “coal-to-power” transition accounts for 20%–30% through government centralized procurement; and real estate developers account for 5%–10% of total sales but are showing a gradual yet significant upward trend. With the policy window of the “coal-to-power” transition coming to an end, heat pump producers should focus on retail and real estate developers.

Cost-effectiveness and product usability are the most critical factors affecting users’ heat pump purchasing decisions, and comparing costs is usually the first thing users do when selecting heat pump products. In addition, local environment, construction conditions, user habits, and several other factors are also considered when determining heat pumps’ usability in buildings. Cost-effectiveness, usability, and users’ understanding and awareness of heat pumps are all key to opening the market.

Saving energy, saving money: Heat pumps' winning card

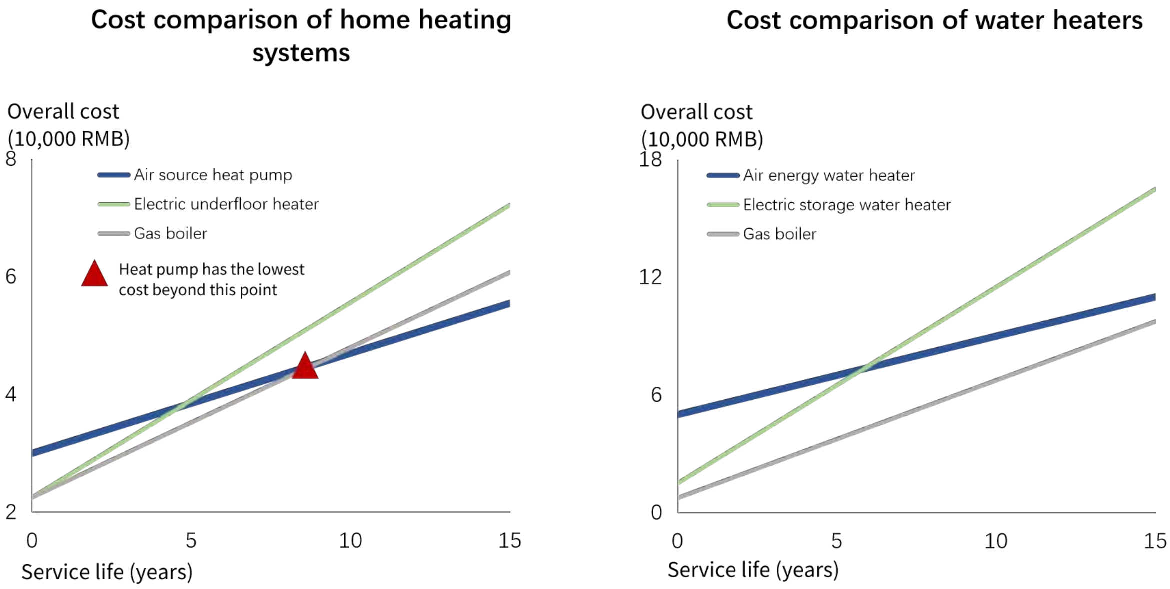
When analyzing the cost-effectiveness of heat pumps, both up-front cost and operational cost need to be considered. The up-front cost consists of equipment cost and installation cost. For heat pump products for space and water heating applications, major factors determining the up-front cost include:

Equipment cost: Heat pump prices are mostly determined by capacity if brand and technology conditions are similar. Users will choose a suitable capacity for space heating based on heating area, local climate and temperature, building insulation, and lighting conditions. The choice of heat pump power level for water heating is mainly determined by such factors as the volume of the water tank and local climate and temperature.

Installation cost: The installation cost of a heat pump for space heating (mainly in the form of an air source heat pump water-based heater for underfloor heating or radiators) depends on whether the original building has heating facilities and to what extent the existing facilities can be used. If the building already has a heating duct system, installation costs will be relatively low. The fan system used in a heat pump is similar to the fan system in an air conditioner, which is quite simple to install. For newly built systems, the air source heat pump installation cost is significantly lower than water and ground source options because no wells or buried pipes are needed. The installation difficulty of a heat pump water heater is also quite low; only the space needed for the water tank is a critical factor.

Operational cost: The operational cost of a heat pump is determined by the unit power price and total power consumption. Factors affecting the power consumption of the heat pump for space heating include heating duration, energy efficiency level[ix], indoor and outdoor temperature difference, and building insulation performance. When other conditions remain constant, the longer the heating time, the lower the energy efficiency level, the greater the indoor and outdoor temperature difference, and the worse the thermal insulation performance, the higher the power consumption of a heat pump for space heating. The power consumption of a heat pump for water heating is mainly affected by water temperature, energy efficiency level, and external environment temperature. As technology gradually matures, the cost competitiveness of the heat pump will continue to improve. Exhibit 13 shows the comprehensive cost[x] comparison of general residential space and water heating equipment.

Exhibit 13: Comprehensive cost comparison of general residential space and water heating equipment (illustrative)



RMI Graphic. Source: Literature research

Space heating: For people who live in new residential buildings, heat pumps are usually a better choice than traditional heating in terms of cost, including the up-front cost and operational cost. Although the up-front cost of installing a heat pump is RMB 10,000–20,000 higher than that of traditional electric underfloor heaters and gas-fired boiler systems, operational cost savings can recover up-front cost overspending within 5 to 10 years.

Water heating: For consumers with an air source heat pump water heater, when household water consumption is moderate and not subsidized, the total cost may catch up with that of an electric water heater in 5 to 8 years, but it could be difficult to catch up with that of a natural gas water heater with a service life of 10 to 15 years. The cost advantage of an air source heat pump water heater may increase significantly if daily water consumption is large enough and in the case of a higher commercial power price.

In reality, however, consumers are more likely to base purchase decisions on up-front cost than total cost, and early users face a higher risk with new products. In terms of cost-effectiveness, if the up-front cost can be

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[ix] It is normally expressed as nominal heating coefficient of performance (COPh)

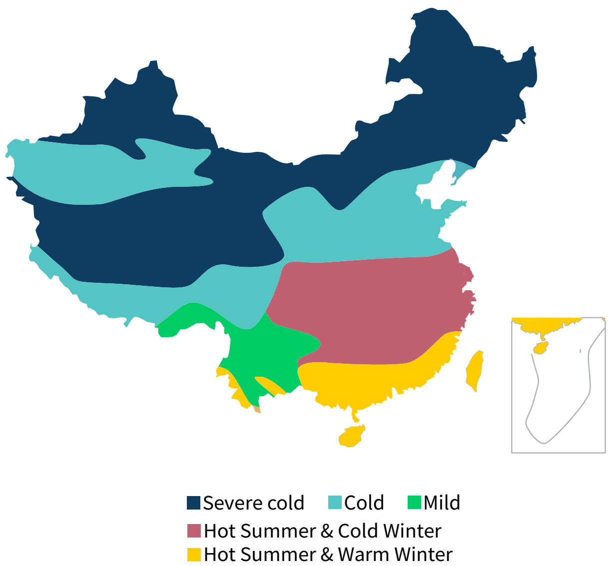
[x] Comprehensive cost is the sum of up-front cost and operational cost, which does not take into account future energy price variation and discount factors

further reduced or more favorable low-carbon subsidies are applied, consumers will be more willing to buy or switch to heat pump products.

Tap the potential: Heating demand in regional markets

China spans many latitudes and covers different climate zones, which leads to varying heating demands and heating conditions in different regions. As shown in Exhibit 14, China has five climate zones: severe cold, cold, mild, hot summer and cold winter, and hot summer and warm winter. Severe cold and cold areas are mainly north of the Qinling Mountains–Huaihe River Line and the Qinghai-Tibet Plateau, with long and cold winters that require long heating time (centralized residential heating systems in most large and medium cities have already been built). The areas with hot summers and cold winters have cooling needs in summer and heating needs in winter, and there are typically no indoor heating networks in these areas. Heating demand is weak in areas with hot summers and warm winters.

Exhibit 14: **The Five major climate zones in China**



RMI Graphic. Source: Tsinghua Building Energy Conservation Research Center, China Building Energy Annual Report 2019

For categorized discussion, in this chapter, China can be divided into three groups according to region and heating style: northern areas with central heating networks, northern areas with distributed heating systems, and southern areas with hot summers and cold winters. Currently, northern areas with distributed heating and the southern areas with hot summers and cold winters are targeted markets for heat pumps.

Northern areas with central heating network

These areas mainly include large and medium cities in North China, Northeast China, and Northwest China, and most heating demands come from medium- and high-rise buildings with existing heating network facilities provided by district heating companies. Most of the management departments prohibit individual modification of the heating facilities to prevent damage to the hydraulic balance of the system. In addition, domestic hot water in these areas is mainly supplied by residential or commercial private electric/gas water heaters.

Space heating: It is difficult for existing retail heat pump products to penetrate the space heating market, where major opportunities exist for absorption heat pumps to replace original central heating. Absorption heat pumps promoted by district heating companies to recover flue gas, steam turbine, and industrial waste heat for heating might greatly reduce fossil-fuel combustion. Currently, available waste heat resources from power plants and industrial facilities in China can meet the heating demand of about 17 billion square meters, which could fully cover the heating needs of areas with central heating systems. The absorption heat pump is relatively mature, and its further penetration mainly depends on the improvement of the management mechanism of waste heat use, and a better solution for cost-effectiveness problems in heat extraction, storage, and transport.

Case study:

To reduce air pollution, the Beijing Heat Import project involved the cooperation and coordination of multiple governments and thermoelectric authorities in Beijing, Tianjin, and Hebei. It used a "4 gas thermoelectric centers + distributed gas-fired peak supply + several waste heat recovery sites" approach to explore the waste heat resources within the Beijing, Tianjin, and Hebei regions with the support of large-temperature-difference and long-distance heating transferring technologies, and has begun to use resources from Sinopec Yanshan Petrochemical Company, Jizhou Datang Panshan Power, and Jizhou Guohua Panshan Power.

Water heating: Air water heaters are rarely an option for residential consumers in either new or replacement installations. Because the air water heater is designed to work at temperatures above 0°C and the temperature in northern China is low in winter, the water heating tank needs to be installed indoors, which is a challenge because water tanks are usually quite large. In addition, problems with the air water heater in the current market are low consumer awareness and high price, often several times higher than that of traditional gas-fired and electric water heaters. Even with energy-saving subsidies of several hundred RMBs, overall consumer acceptance is limited.

Large commercial buildings with independent heating demand may become the breakthrough for heat pump promotion in the trigeneration producing system of cold, warm, and hot water. Commercial buildings, such as hotels and shopping malls, have higher hot water demand and are required to install independent heating systems instead of using centralized heating networks. Therefore, trigeneration system air source heat pumps may be a better choice under the conditions of a high commercial power price and large demand for hot water. For example, Wangfujing Oriental Xintiandi Plaza, an integrated commercial and hotel building in Beijing, is equipped with a 10-ton hot water tank with heating and cooling air source heat pumps to satisfy the demand for hot water at the same time as space cooling and heating.

Northern areas with distributed heating

Northern areas with distributed heating mostly include small towns and rural areas in the north, dominated by residential buildings with many scattered bungalows and short buildings. In these areas, heat pumps can be promoted in retrofit programs to replace central heating heat sources in some areas with dense populations, including specific towns and residential areas. For individual space heating, air source heat pumps already have been adopted by some users because of subsidies provided by a previous "coal-to-power" switch program.

Space heating: In terms of technology R&D, major technical routes to improve low-temperature heating capacity include air injection enthalpy-increasing, two-stage compression, and refrigerant innovation. At present, the COP of conventional air source heat pump products with frequency conversion and air injection enthalpy-increasing can still reach above 2.2 where the low temperature in Northeast China is below -12°C in winter.

Now that use effect and power consumption under low outdoor ambient temperature issues have been solved technically, further progress should focus on product promotion and updating supporting services. With the help of subsidies, air source heat pump products in these areas could have a cost-effective advantage. However, because the distribution of residents in these areas is less concentrated than in cities, accessibility of services such as installation and after-sales support is also critical and can affect the competitiveness of heat pumps in these areas.

Case study:

To ensure after-sales service for heat pump users in northern rural areas, Haier Group plans to increase the granularity of its service, refining after-sales service outlets in villages to pursue the service speed of "48 minutes response and 2 hours door-to-door service," to quickly solve service problems for heat pump users.

Water heating: These areas have less development opportunity for heat pump water heaters. Compared with large and medium cities in northern China, habitants in these areas generally have lower education and income levels, leading to lower market awareness of heat pump water heaters and higher sensitivity to price. Moreover, the number of commercial buildings in these areas is also smaller, leading to a slower promotion of heat pump water heaters in these areas.

Southern areas with cold winters and hot summers

Areas south of the Qinling Mountain–Huaihe River Line are not covered by central heating, whereas southern provinces such as Jiangsu, Anhui, Sichuan, and Guizhou still have long and cold winters. As of 2019, about 30% of residential units are equipped with heating facilities in these areas and about 70% of commercial buildings. RMI estimates that by 2050, these areas will be fully covered by heating services. Under the zero-carbon scenario, heat pump technology will have obvious advantages in these areas and will have significant potential for growth.

Space heating: New residential compounds and commercial buildings can choose air source heat pumps or centralized water and ground source heat pumps systems, according to local conditions, while older residential communities without heating facilities can consider air source heat pumps. Because the average temperature in the coldest winter month in these areas is usually around 0°C, normal temperature air source heat pumps can be used. Users could consider replacing full package gas boiler/electric underfloor heating and cooling air conditioning with heat pumps based on cost-effectiveness.

An air-source heat pump is still an important option for individual residential users. To increase installation convenience, we suggest reserving space for heat pump installation in the design and construction stages of a building, and ensuring that products improve integration of the building's operating system meet the functional needs of users. If water and ground source heat pumps could be deployed in residential buildings, special attention should be paid to the groundwater recharge problem to ensure that the connection between the pump duct and the well pipe is well-sealed.

Centralized procurement for developers of residential and commercial buildings relies heavily on the planning of plots and buildings by design institutes and real estate companies. Design of space and pipe networks for air source heat pumps, arrangement of pipe layout and well drilling for ground source heat pumps, and communication and cooperation with power suppliers can all increase the cost competitiveness of heat pump products.

Case study:

Heat pump heating has become a trend in newly developed properties. For example, a new residential compound in Hongqiao, Shanghai, is selling new properties equipped with heat pumps, promoting the concepts of fashion, environmental protection, and comfort as well as a potential 40%–50% energy savings. Additionally, many southern cities along rivers, including Chongqing, Changsha, and Nanjing, have used river water source renewable energy stations, providing centralized heating and cooling for their business districts through water source heat pumps. These projects have become the highlights of the cities 'green and low-carbon practices.

Water heating: Because of relatively mild winter temperatures and better affordability, penetration of air water heaters in the southeast coastal areas of China is relatively high. Further market penetration requires more attractive costs and more precise and powerful marketing approaches.

Like northern cities, new buildings in these areas, especially commercial buildings, might also consider heat pumps with a trigeneration-producing system of hot, warm, and cold water, based on their actual hot water demand, to save energy.

3. Zero-Carbon Steel "Core": Iron Ore Electrolysis Technology Outlook

The steel sector is one of the world's leading carbon contributors, accounting for nearly 10% of global carbon emissions. China is the largest producer and consumer of steel in the world, responsible for more than 50% of global production and consumption each year. In 2019, 17% of China's carbon emissions came from the steel sector, and more than 70% of carbon emissions in the steel industry were from the blast furnace iron pretreatment process in traditional long-process steelmaking.

China's carbon neutrality goal cannot be realized without deep decarbonization of the steel sector, largely driven by improvement and replacement of traditional steelmaking technology and R&D into low-carbon and zero-carbon steelmaking technology. In this insight brief, we provide a deep review of iron ore electrolysis technology, a highly disruptive steelmaking decarbonization technology, especially when it comes to its development and status in the European and American markets. We also analyze the technology's challenges and opportunities in China, hoping to attract readers' attention and thinking, and provide a quick scan of its current status and future prospects. Some basic facts and observations are as follows:

(1) As a disruptive primary steelmaking technology with great carbon reduction potential (could achieve more than 95% carbon emissions reduction), iron ore electrolysis technology has been vigorously developed in Europe and North America for nearly 20 years, but no pilot or planning of this technology has been explicitly proposed by Chinese steelmakers.

(2) Molten oxide electrolysis and low-temperature electrowinning are the two major iron ore electrolysis technologies with commercial prospects, developed by Boston Metal in the United States and the Σiderwin project in Europe, respectively. The former is funded by a startup founded by researchers and industry experts, whereas the latter is coordinated by steel giants with official EU funding for low-carbon technology research.

(3) According to major technology research institutes and company plans, iron ore electrolysis technology will be commercially deployed after 2030. The rising price of carbon and declining renewable power costs will enable this technology to grow in market size to about 5% of global steel production by 2050.

(4) Major challenges to further adoption of iron ore electrolysis include technology maturity, access barriers, and availability of power supply. Therefore, close attention should be paid to technological trends, breakthroughs in key technology bottlenecks, and innovative power supply solutions.

Please continue reading the full article for more details, and you are welcomed to discuss any contents or topics of interest with us.

Iron Ore Electrolysis: Most Promising Technology for Zero-Carbon Steel

Since the mid-20th century, dozens of new steelmaking technologies have been studied and proposed, some of which have entered a pilot or industrial application stage, especially in the context of global decarbonization. In *Pursuing Zero-Carbon Steel in China: A Critical Pillar to Reach Carbon Neutrality*, RMI summarized the current mainstream decarbonization technologies in the steel industry and indicated that the most outstanding technologies are disruptive primary steelmaking technologies with large emissions-reduction potentials, including hydrogen direct reduced iron (DRI), hydrogen plasma smelting reduction, and direct electrolysis. Chinese steelmakers have piloted or planned for the former two technologies, although an explicit development plan for the iron ore electrolysis technology has not yet emerged.

Since 2004, the European Ultra Low CO2 Steelmaking (ULCOS) program has explored iron ore electrolysis technology, with molten oxide electrolysis (MOE) and low-temperature electrowinning being widely accepted as the most promising pathways.

Although iron ore electrolysis technology is relatively immature, studies have made rapid progress in recent years because of its lower requirements for raw ore grade and its high economic competitiveness potential. In terms of decarbonization, the emissions reduction potential of iron ore electrolysis could reach about 95% in the zero-carbon power grid scenario. In addition, the technology offers two technical routes with different advantages in terms of cost competitiveness and iron ore grade requirements.

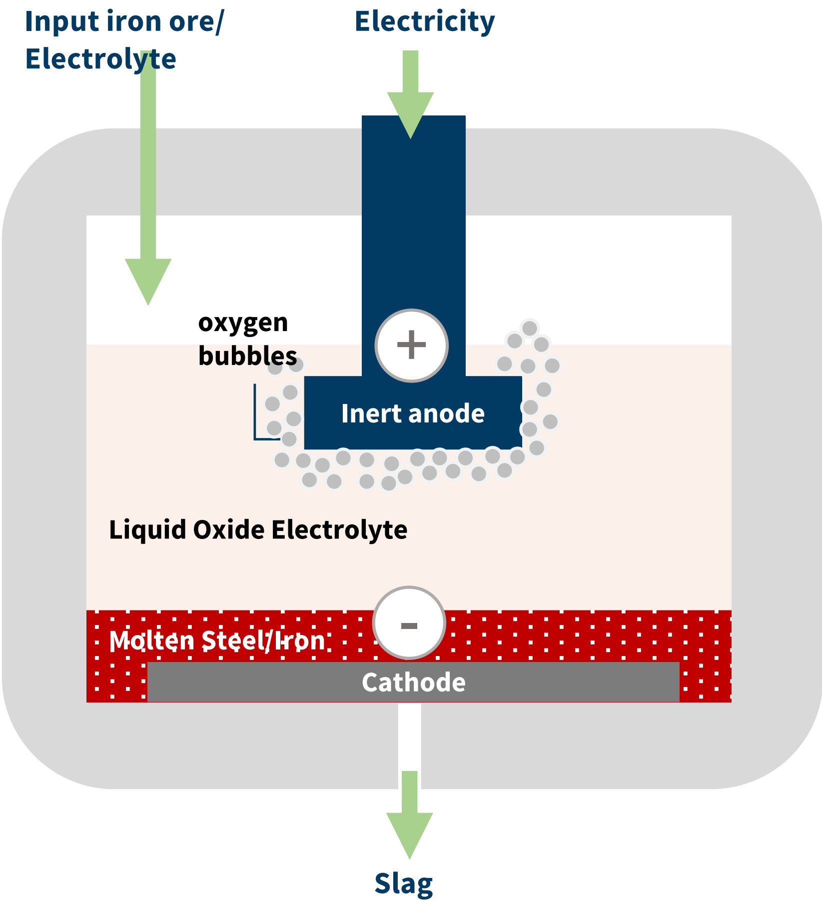
As for low-temperature electrowinning, due to its relatively simple equipment technology and low energy consumption, total cost per ton of steel is expected to be competitive with hydrogen DRI by 2050. According to Agora, the overall cost per ton of steel for low-temperature electrowinning is estimated to be EUR 645–828 (about RMB 4,500–5,800) in 2050, which is generally in the range of RMI's analysis showing a price of under RMB 30/kg hydrogen in 2050. As for MOE, the ultra-high-temperature environment has a lower requirement for raw ore grade, and the technology's requirement for the iron content of raw ore could be decreased from higher than 65% to about 55% compared with current hydrogen DRI, according to Boston Metal.

Focus on Two Technical Routes of Iron Ore Electrolysis Technology

MOE

Boston Metal has been leading research into MOE technology, showing a technology readiness level (TRL) of between 4 and 5, and is currently in the engineering validation stage. As shown in Exhibit 15, the metallurgical technology enables metal to be deposited on an electrode through molten electrolysis. Being a completely electrified primary steelmaking technology, it doesn't need the addition of a carbon-containing reducing agent compared with traditional steelmaking routes, such as blast furnace–basic oxygen furnace (BF-BOF), and is a disruptive low-carbon technology that theoretically can reduce Scope 1 emissions to zero. This technology will have great potential for emissions reduction during the deep decarbonization of the power grid.

Exhibit 15: **Schematic diagram of an MOE electrolyzer**



RMI Graphic. Source: Literature review, RMI analysis

Without the need to pretreat iron ore, including crushing, screening, separation, and agglomeration, iron ore and oxide electrolyte (such as silicon, magnesium, or calcium oxide) are put into the electrolyzer, electrified, and heated to a molten state at nearly 1,600°C. With an anode and a cathode at the top and bottom of the container, respectively, the electric current enables oxygen ions in the molten substance to react at the anode, generating oxygen gas to be released. Meanwhile, iron ions are reduced to molten iron at the cathode, which can be refined into steel or used directly.

The principle of molten salt electrolysis of metal is not new. It has been widely used in aluminum, magnesium, and other metal smelting industries for a long time, but the application of this technology to steelmaking is a breakthrough. However, because of the high melting point of iron, one of the biggest challenges has been to ensure the stability of the electrode material in the electrolyzer under conditions of high temperature and corrosion. Donald Sadoway, cofounder of Boston Metal, and his team have developed a chrome-iron alloy anode material that can react at nearly 1,600°C to form an oxide film on the surface, protecting the underlying metal and leaving it largely unreactive with the molten material in the electrolyzer and oxygen generated near the anode. This breakthrough technology offers a relatively affordable choice of electrode materials for high-temperature molten electrolysis of iron ore, paving the way for large-scale development.

Although the problem of chemical reaction in electrolysis has been solved, the scaled deployment of this technology still faces many problems. For example, inert anode materials are still undergoing large-scale engineering validation, and the search for better electrode materials is continuing. In addition, the heating and insulation process consumes a lot of power and is difficult to interrupt, which leads not only to high energy consumption and cost, but also may put pressure on the power grid in areas with a tight power supply in large-scale development. In areas where the carbon emissions levels of the grid are still high, this technology does not even have obvious carbon emissions-reduction advantages compared with other low-carbon routes if full life cycles are compared. Exhibit 16 compares the major stages from iron ore to molten steel in different steelmaking processes.

Exhibit 16: Major stages from iron ore to molten steel in different steelmaking processes

		Pretreatment		Ironmaking	Steelmaking
		Ore selection	*Agglomeration*	*Iron reduction*	*Molten iron with impurities*
	Carbon emission share of each step in BF-BOF based long-process steelmaking (Sum total is less than 100% as refining and reducing agent processing excluded)	<10%	~25%	~40%	<10%
	**BF-BOF**	Crushing, screening	Sintering, pelleting	BF reduction	BOF ironmaking
	**Gas-based shaft furnace — EAF** (Natural gas/H2)	Crushing, screening	Pelleting	Shaft furnace reduction	EAF ironmaking
	**Waste steel recovery**	Crushing, smelting			EAF ironmaking
	**MOE**				MOE
	**Electrowinning**	Crushing, screening		Electrowinning	EAF ironmaking

RMI Graphic. Source: Literature review, RMI analysis

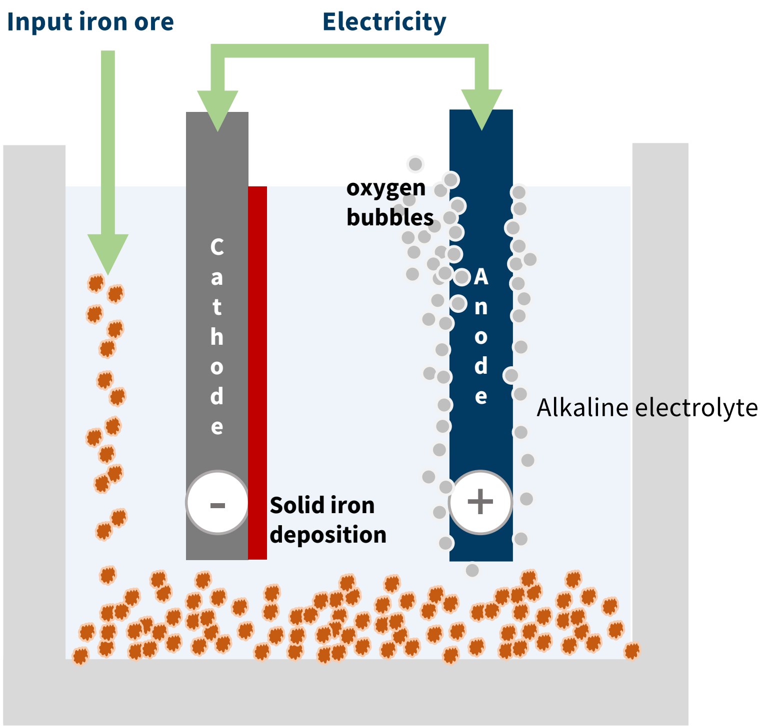
However, it is worth mentioning that the MOE process has a unique advantage in the use of relatively low-grade raw ore because of its disruptive innovation compared with traditional steelmaking routes. Because iron ore does not need pretreatment, and the extreme high-temperature environment can create better reduction conditions, the requirement for the grade of iron ore is less stringent. Compared with other low-carbon steelmaking technologies, such as the most popular hydrogen DRI combined with an electric arc furnace (EAF), MOE can lower the grade requirement of iron ore by about 10%, which may reduce dependence on high-grade imported iron ore and enhance the safety and stability of the raw material supply chain.

Low-temperature Electrowinning

The Σiderwin Project, led by ArcelorMittal, is conducting research into low-temperature electrowinning with a TRL of between 5 and 6, and engineering-scale pilot projects currently are under construction. This is an ironmaking technology in which iron ore is deposited directly on the electrode in an electrolyzer filled with alkaline solution at about 110°C. Because the required heating temperature is low, the energy consumption level of this technical route is less than 70% of that in BF, and there is no need for continuous heating, which means an intermittent off-peak power supply can be used. As a completely electrified steelmaking process, this technology and MOE have considerable decarbonization potential (Exhibit 17).

Low-temperature electrowinning can be divided roughly into the following steps. Before entering the electrolytic reduction step, the iron ore needs to go through pretreatment processes, such as grinding, screening, and ore washing to ensure the full progress of the electrolytic reaction. After electrolysis, solid sediment of nearly pure iron is obtained and then enters an EAF to be heated and refined into steel. Electrolysis is the key step in this process: The electrolyzer is filled with high alkaline sodium hydroxide solution at about 110°C with a stainless-steel cathode and pure nickel anode positioned on the left and right sides, respectively. After the iron ore particles are put into the electrolyzer, a current passes through the electrolyte solution to form the reaction, with iron ions in the solution reduced and deposited on the cathode surface and hydrogen and oxygen ions reacting at the anode to produce water and oxygen.

Exhibit 17: **Schematic diagram of a low-temperature electrowinning electrolyzer**



RMI Graphic. Source: Literature review, RMI analysis

Research into this technology has focused on improving the Faraday efficiency and reaction rate of the electrolysis process.[xi] Through testing different current intensity, voltage level, electrolyte composition, and ore grade in the laboratory, the Faraday efficiency of the process can reach an ideal level of higher than 90%. To improve the reaction rate of electrolysis, one of the major technological breakthroughs the Σiderwin project was looking for was how to accelerate the release of oxygen bubbles at the anode, preventing the decrease of the reaction rate due to the weakening of the conductivity of the solution. Through computational fluid dynamics simulation technology, the project team specially designed the deployment angle, exhaust device, and pressure control of the electrolyzer, which improved the release rate of oxygen.

According to the Green Steel for Europe Consortium, future research on low-temperature electrowinning should aim to expand the scale of the electrolyzer and achieve simultaneous operation of multiple electrolyzers. Although the technology has begun to move from laboratory to industrial scale, the full capacity of the Σiderwin project is still as low as 100 kg of pure iron every 48 hours. Therefore, increasing yield of a single reaction to guarantee efficiency and the rate of reaction is key to expanding production to reach industrial scale. In addition, future development directions include further improving ease of use and economy of the device by optimizing the design of intelligent control, oxygen recovery, and the slag removal mechanism.

According to current planning at major research institutions and companies, iron ore electrolysis technology will be commercially deployed after 2030. With the rising carbon price and the further cost reduction of renewable power, the technology is expected to be expanded from pilots in Europe and the United States to other regions by 2050, accounting for about 5% of the world's steel output and becoming one of the most important zero-carbon steelmaking approaches, in addition to hydrogen metallurgy.

In terms of technological development, iron ore electrolysis technology is expected to achieve commercialization in the 2030s. According to the Green Steel for Europe Consortium, the TRL of iron ore electrolysis technology could reach 9 around 2040, which could fully meet customer demand for delivery and enter the commercial deployment stage. Although there is still room to improve in terms of cost competitiveness, the technology will become one of the major steelmaking routes globally. Businesses are relatively optimistic, with commercial plants expected to be deployed around 2030. According to Boston Metal's plans for MOE, a verification pilot program will be completed by 2023, and a demonstration plant with an annual production capacity of about 25,000 tons will be established by 2025, with commercial operation starting by 2030 at the latest.

Σiderwin estimates that a commercial plant of low-temperature electrowinning will be deployed by 2030 at the latest, with annual production capacity reaching around 50,000 tons and eventually rising to 1 million tons. (In comparison, annual production of ArcelorMittal was 79 million tons in 2021.)

The cost per ton of steel will still be a competitive weakness of direct electrolysis technology even after commercialization is achieved. At present, the overall cost of crude steel produced through traditional

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[xi] Faraday efficiency is one of the ratios used in electrochemistry to measure the efficiency of a reaction. It equals the ratio of the actual product to the theoretical product, expressed here as a percentage.

long process is about RMB 3,000–4,000 per ton. According to Agora's outlook, the overall cost per ton of steel of low-temperature electrowinning will be about RMB 4,500–5,800 in 2050, with shares of capital expenditures and operating expenditures at 25% and 75%, respectively. As for MOE, power consumption per ton of steel is currently about 4,000 kWh and there's limited room for improvement through process optimization. Based on the global average industrial power price of about RMB 0.9/kWh, the operating cost including other auxiliary materials is estimated to be about RMB 4,000. The estimated overall cost per ton of steel may reach RMB 5,000 with shares of capital expenditures and operating expenditures also at 25% and 75%, respectively.

In terms of decarbonization potential, direct electrolysis technology has absolute advantages and may become more attractive in the future when the carbon price rises. Current long-process (BF-BOF) steelmaking has an emissions level of about 2 tons of CO_2 per ton of steel. In comparison, the Σiderwin project may reduce emissions intensity by about 30% and has potential to further reduce emissions by 50%–80% by 2050, depending on the renewable power ratio of the grid. RMI estimates that Boston Metal's MOE technology may achieve an emissions reduction of up to 95% in a zero-carbon grid. Therefore, assuming the carbon market is fully functional in the steel industry by 2050, direct electrolysis technology could reduce 1 to 1.5 tons of carbon emissions per ton of steel compared with traditional steelmaking, reaching price parity with the latter when the carbon price is higher than RMB 1,000/ton.

Development Prospect of Iron Ore Electrolysis Technology in China

Chinese steelmakers are global leaders in terms of production output and have financial and policy advantages in the development of low-carbon steelmaking technologies. Iron ore electrolysis technology has great potential for steel decarbonization and supply chain security, and we believe this technology deserves close attention from Chinese steelmakers and could be added to their list of technologies to be developed. For Chinese steelmakers looking to build their own technical capabilities in iron ore electrolysis technology, Boston Metal and the Σiderwin project may provide two very different development models for reference.

Boston Metal is a startup that was founded by researchers and industry experts in 2013. Within less than a decade, it has raised about $85 million in two rounds of funding. A typical research company, its fundamental technology is an inert anode material suitable for high-temperature smelting electrolysis of iron ore, developed by Donald Sadoway, one of the company's cofounders and a professor emeritus at the Massachusetts Institute of Technology, and his team in 2010. The work was published in *Nature* in 2013, and an electrolytic steelmaking pilot line began to operate and obtained patents in 2014.

Boston Metal received $600,000 from the National Science Foundation in 2015 and raised two rounds of financing of about $20 million in 2018 and $60 million in 2021. The number of employees increased from 8 in 2018 to 65 in 2021, and Boston Metal now has several senior managers from investment funds on its board. A venture capital fund managed by BMW, a potential client, participated in 2021's financing. Boston Metal is likely to rapidly improve its business model, customer relations, and management efficiency going forward.

As a five-year (2017–22) low-carbon technology research project funded by the Horizon Europe Program, the Σiderwin project is led by Luxembourg-based steel giant ArcelorMittal with total funding of EUR 6.8

million, and its 12 upstream and downstream partners come from seven EU countries. The project is led by ArcelorMittal's Hervé Lavelaine, who has headed several low-carbon steelmaking technology research programs (ULCOS, ASCoPE, IERO, VALORCO, etc.) or their electrolytic ironmaking branches in Europe over more than 10 years. The Σiderwin project is also an extension of the low-carbon steelmaking programs, meaning the total accumulated R&D investment in the low-temperature electrowinning technology far exceeds the funding amount of the Σiderwin project, but the technology has made significant progress during this project. A pilot project of low-temperature electrowinning started construction in Maizières, France, in 2019, had its equipment commissioned in early 2020, and started operations this year.

Competition in China's steel industry is still dominated by giant manufacturers. Top Chinese steelmakers are where resources aggregate, including production capacity, capital, talent, and technology, as well as leadership in the low-carbon transition of the industry. As an emerging industrial country, China's steel industry is still experiencing high consumption, and its carbon emissions have not yet peaked. In addition, as its deployed long-process, steelmaking assets are relatively young, the current low-carbon technology direction is focused on energy saving and efficiency improvement of the existing BF process to avoid stranding a large number of assets.

At the same time, aiming at long-term development, some of the top steelmakers have begun to cooperate with foreign businesses or scientific research institutions and have made progress. At present, Baowu, HBIS, and Jianlong Group are in leading positions in the R&D of disruptive low-carbon primary steelmaking in China. This year, Baowu Group's Zhanjiang Plant started construction of a 1 million-ton hydrogen-based shaft furnace project, looking to make it operational by 2023. The project is using coke oven gas and hydrogen as reducing gas to directly reduce iron in the shaft furnace, with a total investment of nearly RMB 2 billion.

At the end of 2020, HBIS signed a cooperation agreement with Tenova, the world's leading industrial furnace manufacturer, to jointly build China's first Energiron DRI plant, with reducing gas gradually converted from coke oven gas to green hydrogen in the later stage. Upon completion, the plant will have an annual capacity of 1.2 million tons of steelmaking raw materials. In 2019, Jianlong Group cooperated with the University of Science and Technology Beijing and other institutions to invest more than RMB 1 billion to develop the hydrogen-based smelting reduction process after studying various leading technologies globally and successfully localizing key equipment and parts. In 2021, more than 150 tons of iron were successfully produced.

Although the exploration and practice of disruptive primary steelmaking technologies by Chinese steelmakers is limited at present, the direction of the low-carbon transition of the industry will not change, and the capability of low-carbon technologies in the medium to long term may be at the core of steelmakers' competitiveness in the future. Although the development of iron ore electrolysis technology in China is still in its infancy, we believe top steelmakers will continue to work on its deployment. At present, publicly available information shows that molten oxide zero-carbon electrochemical ironmaking technology was mentioned by the Baowu Group in the launch of the 2021 Global Low-Carbon Metallurgy Innovation Fund Program. In addition, the global Low-Carbon Metallurgy Innovation Alliance, led by the Baowu Group, was set up at the end of 2021, establishing a formal platform for academic and technical exchanges in the steel industry.

Unlike DRI and hydrogen-based smelting reduction, the application and exploration of direct electrolysis in China is still in its infancy, and the main obstacles it faces include:

- *Low technology maturity globally:* with TRL below 6, MOE and low-temperature electrowinning are still undergoing laboratory tests or small-scale production trials and are in the key stage of technology and engineering breakthroughs, facing uncertainty in scaled expansion.

- *High barriers to entry:* Boston Metal and ArcelorMittal have established high barriers to entry through long-term development in this technology, and latecomers trying to replicate this path will face constraints such as patents, talent, and supply chain.

- *Strict requirement on power supply:* Because of the high energy consumption needed by the electrolytic iron ore reduction solution and its high demand for power supply, especially the demand for an uninterrupted power supply in MOE technology, the establishment of large-scale pilot projects or commercial plants will have to consider multiple factors such as local power price, the availability of renewable power, and power load (if grid power is used).

Given that Chinese steelmakers started to introduce hydrogen metallurgy technology when its TRL level was between 5 and 9, it can be estimated that the start of cooperation in direct electrolysis technology or the TRL threshold of technology introduction will be triggered soon. Therefore, Chinese steelmakers aiming to deploy this technology in the medium to long term should focus on efforts in the following directions:

- Keep a close eye on technology trends: Establish the ability to monitor technology intelligence and the latest R&D processes of global cutting-edge technologies to stay informed when timing technology introductions.

- Breakthrough key technical bottlenecks: When the decision is made to deploy this technology, breakthroughs in key technical bottlenecks and patents should be made through investment or cooperation with foreign equipment suppliers, or the establishment of a local team to develop key equipment and components.

- Innovative solutions for power supply: In the early stage of project planning, the total amount and intensity of power consumption should be fully considered, and projects should be deployed in areas with abundant and cheap renewable power resources. With a low requirement for power stability, low-temperature electrowinning technology should be considered at on-site, self-built power generation facilities, whereas the demand for an uninterruptible power supply by MOE technology could be deployed in areas with more favorable local pricing policies and power grid conditions.

4. Zero-Carbon “Reaction”: Examining Flow Battery Energy Storage

Energy storage is the strategic pivot of energy transformation. In the process of achieving the dual carbon goals, China is bound to face a period of large-scale development of wind and solar. A cost-effective, safe, and reliable energy storage technology is an important basis to ensure the stable operation of the power system with rapidly increasing wind and solar capacity. The energy storage industry has recently received special attention from the government, the market, and the academic community, with numerous efforts made to explore various types of energy storage technologies and continuous discussions on factors including cost, safety, capacity, and applicability.

By sorting out the information and observations on the energy storage market, this insight brief focuses on various technical routes and application cases from new energy storage to electrochemical energy storage, and further to flow battery technology, hoping to help readers understand the current status of the flow battery as one of the energy storage technologies in China and identify its future development directions. Some basic facts and our observations are as follows:

(1) The rapid development of the energy storage market is closely related to the vigorous expansion of renewable power generation, and energy storage is considered an effective solution for regulating the volatility of renewable output. New energy storage technologies, especially electrochemical energy storage technologies, have the strongest growth trend and prospects.

(2) As a niche technology category in electrochemical energy storage, the flow battery stands out for its safety and durability. Even with a relatively high price, it is penetrating a variety of application cases.

(3) Among the mainstream technical routes of all types of flow batteries, the Vanadium Redox Flow Battery (VRFB) has the highest maturity and market share. With a leading position in terms of commercialization, its advantages in supply chain stability and domestic substitution of key components are major barriers that other technical routes would find difficult to compete with in the short term.

(4) In the future development of the flow battery in China, further scaling and cost reduction driven by substitution of key components are the top priorities. In addition, actively guiding the release of supporting policies and their continuity and stability cannot be ignored to boost the rapid scale of the industry.

Booming Energy Storage Market and Strong Growth of New Energy Storage

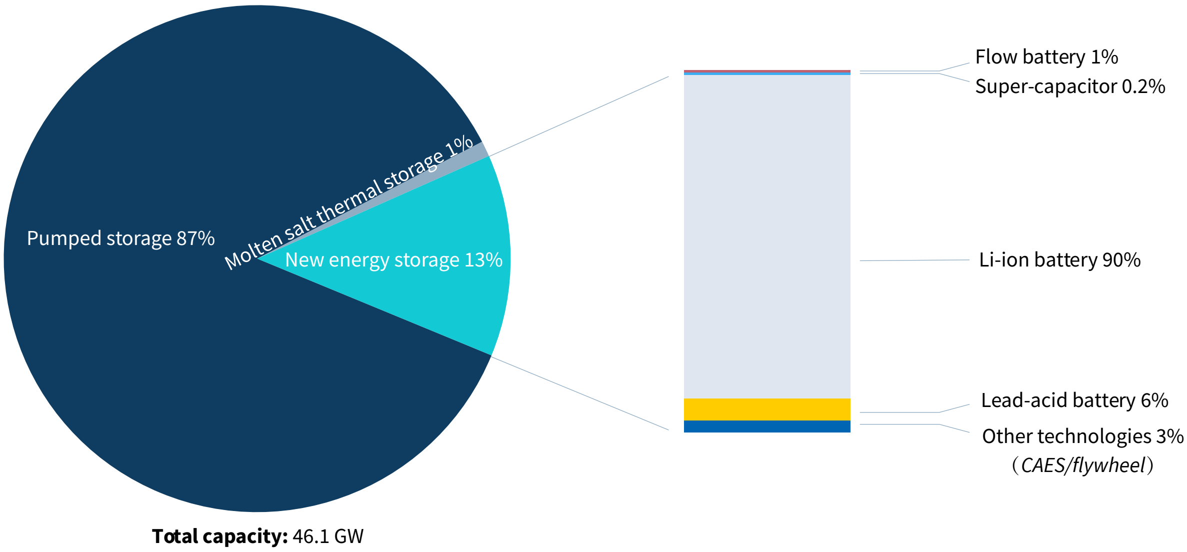
The installed capacity of renewable power in China has increased rapidly in recent years, with additional capacity exceeding 100 million kW in 2021, accounting for 58% of the total additional capacity in the country. With the continuous increase in the share of renewable generation, the inherent variations of wind and solar have brought great challenges to the safe and stable operation of the power grid. Energy storage equipment, like a reservoir, is one of the most effective solutions to flatten the intermittent renewable power supply and ensure the flexible and stable operation of the power grid.

Up to now, most provinces in China have successively issued the requirements for collocated energy storage for newly built renewable generation, and the required storage capacity on the generation side usually accounts for 5%–30% of total installed capacity (averaging 10%) with one to four hours of duration (averaging two hours), paving the road for the future large-scale development of the energy storage market. In addition, demand for energy storage on the grid side and the user side will also be gradually amplified with the increased penetration of renewables.

In the "Action Plan for Carbon Dioxide Peaking Before 2030," the State Council set a target of 1,200 GW of installed solar and wind capacity by 2030. Based on this target, at least 200 GW of energy storage facilities will be needed, according to Guoping Chen, State Grid's chief engineer. Furthermore, it is widely believed in the industry that the actual installed capacity may far exceed the plan. RMI predicted in *Zero Carbon Power Growth (2020–2030)* that by 2030, the total installed capacity of wind and solar will exceed 1,600 GW, and the required energy storage capacity matching this estimate could exceed 250 GW.

According to the Energy Storage Industry White Paper 2022, released by the China Energy Storage Alliance, 46.1 GW of energy storage projects were operating in China by the end of 2021, mostly pumped storage and new energy storage (see Exhibit 18). Installed capacity of pumped storage dominates at 39.8 GW and accounts for 87% of the total. Although new energy storage of 5.73 GW only accounts for 13% of the total, it increased by 74% compared with the same period in 2020, showing stronger momentum. The report conservatively estimates that China's cumulative installed capacity of new energy storage will reach 48.5 GW in 2026, with a compound annual growth rate of more than 50%.

Exhibit 18: **Chinese power energy storage market capacity (MW%, by the end of 2021)**



RMI Graphic. Source: Energy Storage Committee, China Energy Research Society, China Energy Storage Alliance, Energy Storage Industry White Paper 2022

New energy storage installations that contribute the most to the growth of the market include electrochemical energy storage, compressed air, and flywheel energy storage. Electrochemical energy storage includes a variety of mainstream technologies (see Exhibit 19), and though the cost is relatively high at present, it has the advantages of less strict geographical restrictions and shorter project lead time, mainly where the scale is smaller or there is limited access to pumped storage. Lithium-ion batteries, for instance, have achieved significant cost reduction and commercialization in the past decade, taking the lead in the electrochemical energy storage market with a market share of more than 90%, far ahead of other technologies. Lead battery technology is mature, but it is about to be phased out because of pollution problems. Other types of electrochemical energy storage and physical energy storage (such as compressed air and flywheel energy storage) are in the early stages of commercialization with small market shares, but their technical characteristics are different.

Exhibit 19: Comparison of characteristics of major new energy storage technologies

New Energy Storage (non-exhaustive)		Market share*	Description	Advantage	Disadvantage	Representative Chinese businesses
Electrochemical	Li-ion battery	89.7%	Highly commercialized battery with most widely used applications including consumer electronics, EVs and power storage	High energy intensity, high output power and fast startup	Major fire risk, high system cost and recovery cost	CATL 宁德时代; BYD; ZTT 中天科技; 南都电源 Narada
	Lead battery	5.9%	Highly commercialized mature battery technology that is used in transport vehicles and power storage	Low cost and stable output power	Low energy density, short service life and highly polluting	天能动力 TIANNENG POWER; 超威电池; 骆驼电池
	Flow battery	0.9%	Technology in early stage of commercialization that is currently used in power storage	High safety, long service life and can be easily expanded	Low energy density, high system cost	融科储能 RONGKE POWER; PU NENG; ZH 中和储能 ZH ENERGY
	Super capacitor	0.2%	Chemical power source between traditional capacitor and battery that is in early stage of commercialization, mainly used in transportation, manufacturing and power storage	Long service life, high charging/discharging power and fast startup	Low energy density, high system cost and high self-discharge rate	奥威科技 AOWEI TECHNOLOGY; 新筑股份; 巨容新能源
Compressed air		3.2%	The large scale of CAES requires specially built gas storage chamber to convert electric energy into internal energy of air for storage. It's in early stage of commercialization, and it's mainly used in power storage application.	Long service life, long duration and high system efficiency	Strict requirement on geographical condition and long lead time	ShaanGu 陕鼓集团 SHAANGU GROUP; JTLTECH; 中储国能; CEEC 中国能建 ENERGY CHINA
Flywheel		0.1%	Technology that converts electric energy to mechanical kinetical energy of fast-spinning flywheel. It is in scaled trial stage and is used in transportation and distributed energy storage	High power density, long service life and strong environment adaptability	Low energy density and high self-discharge rate	HHE; VYCON 微控

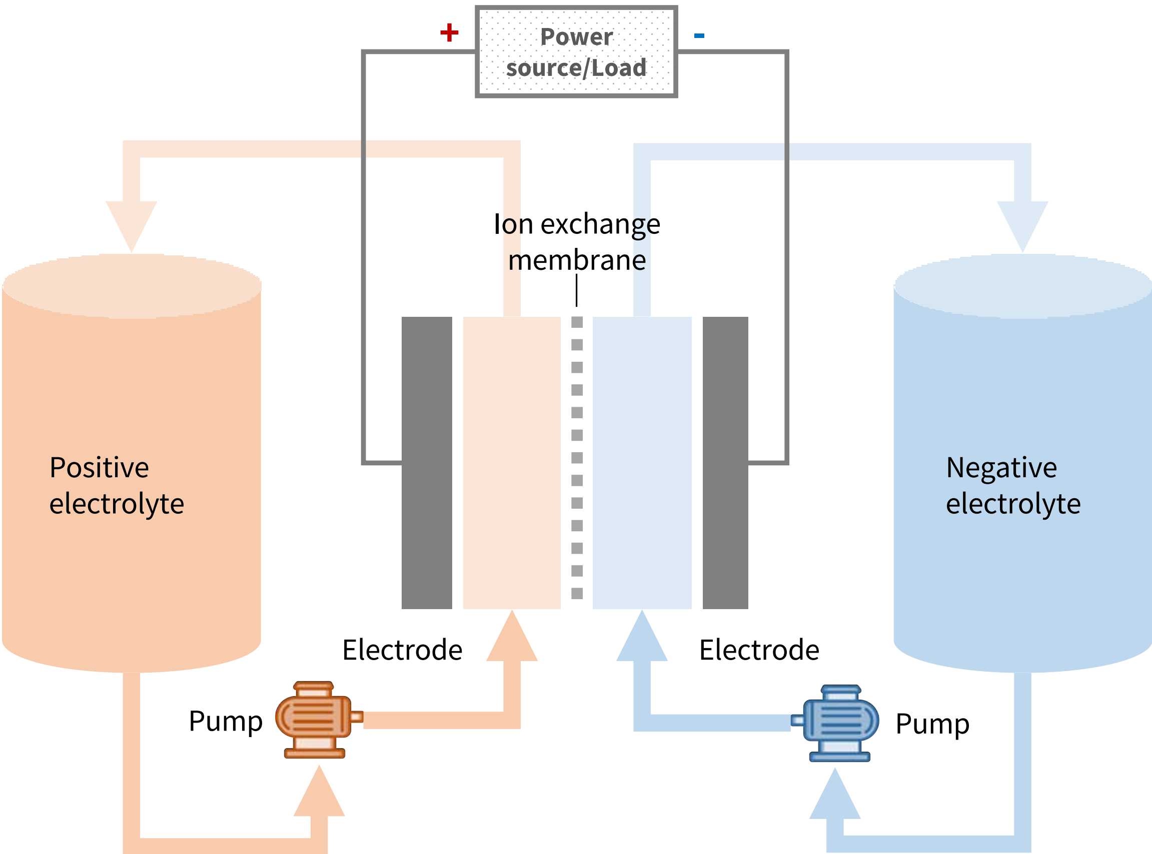
Note: *Energy Storage Committee, China Energy Research Society / China Energy Storage Alliance, Energy Storage Industry White Paper 2022, Share in China's cumulative power storage capacity in 2021 with new energy storage = 1.

RMI Graphic. Source: Literature review, RMI analysis

Flow Battery Is Safe and Durable, with Unique Comparative Advantages

A form of electrochemical energy storage, a flow battery is sometimes called a rechargeable fuel cell, and it works like a fuel cell. As shown in Exhibit 20, positive and negative electrolytes are stored in separate containers, and the connecting part is the power generation area, which is separated by an ion exchange membrane. When the electrolyte is pumped into the power generating area, the electrolyte on each side of the membrane undergoes an ion exchange reaction to discharge, converting the stored chemical energy into electrical energy. Unlike conventional fuel cells, however, if the recovered electrolyte in a flow battery is electrified, it can be reduced through a reversible reaction, converting electrical energy into chemical energy for storage. Therefore, a flow battery has outstanding advantages in safety and service life by virtue of its technical characteristics of space separation of power generation and energy storage and is completely recyclable.

Exhibit 20: **Schematic diagram of flow battery operation**



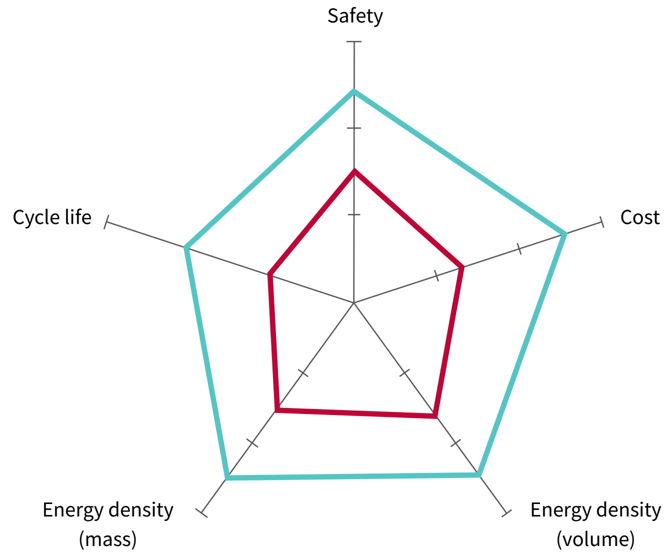
RMI Graphic. Source: Literature review, RMI analysis

The research team conducted a multidimensional comparison of the energy storage performance of lithium-ion batteries and flow batteries (see Exhibit 21). According to the statistics, lithium-ion batteries are high risk in terms of fire and the small number of charge-discharge cycles, whereas flow batteries, with a current market share of less than 1%, perform better in those two risk areas.

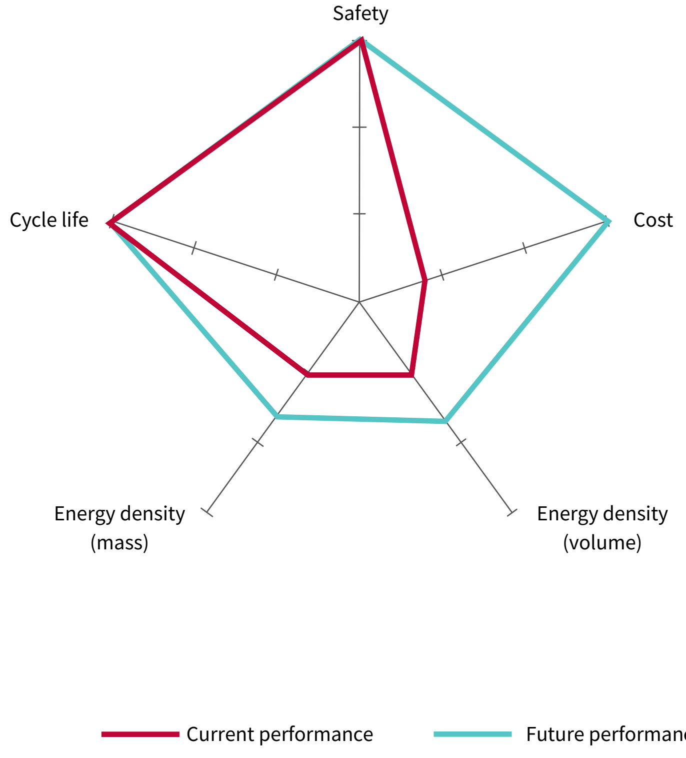
Because space is relatively abundant in applications on both the generation side and the grid side, the disadvantage of the low energy density of flow batteries will not be a key constraint. In addition, due to the limitations of safety and cost, lithium-ion batteries have limited potential to increase storage duration for more than 4 hours, while flow batteries can simply increase duration with the addition of electrolyte to provide up to 12 hours of storage, greatly increasing the contribution of energy storage in terms of flexibility. In addition, given its considerable potential to reduce costs, the flow battery has been promoted as a new generation of innovative technology solutions in the domestic market. Especially with rapidly growing renewable power penetration and ancillary services, flow battery technology is considered one of the mainstream electric energy storage technology routes comparable to lithium-ion batteries in terms of application scale in the future.

Exhibit 21: **Relative performance attributes for Li-ion batteries and flow batteries**

Li-ion battery



Flow battery



RMI Graphic. Source: RMI, *Breakthrough Batteries: Powering the Era of Clean Electrification*, 2019

Flow Battery Technology Has Diverse Branches with VRFB Taking the Lead

Flow batteries are generally classified according to the active substance of the electrode. According to the current commercialization level, four types of flow batteries with good development are VRFBs, iron-chromium flow batteries (ICBs), zinc-based flow batteries, and all-iron flow batteries. VRFBs have the highest commercialization level and the largest installed capacity, accounting for about 70% of the global total. The remaining technologies are all small in scale at present. China is relatively advanced for VRFBs and ICBs.

The commercialization level of different types of flow batteries mainly depends on cost competitiveness and technical applicability. The total cost of a battery is determined by up-front cost, maintenance cost, and service life, and technical applicability is mainly determined by characteristics of the electrolyte, energy density, and safety.

Among different flow battery technologies, VRFB is the most mature, but its suitable operating temperature range is narrow and it cannot work stably in an environment below 0°C without adjustment. Because of the abundant valence state of vanadium ion active substances, vanadium ion solution in high and low valence states is naturally suitable to be used as positive and negative electrolytes as energy storage medium to repeat reversible oxidation-reduction (redox) reactions. At the same time, vanadium is a rare metal, and the price of vanadium ionic electrolyte is much higher than that of other electrolytes that provide the same amount of energy, including lithium, iron, and zinc.

Compared with other substances, vanadium has relatively limited cost-reduction potential and may not have obvious economic advantages. Finally, China leads the world in vanadium ore reserve and output, from the perspective of supply chain security, VRFBs are likely to be more suitable for long-term development and deployment in the Chinese market. China's VRFB manufacturers are in a leading position in the world, with representative companies such as Dalian Rongke Power and Beijing VRB Energy.

The world''s largest flow battery energy storage project was officially connected to the grid in Dalian, Liaoning, in 2022, and it started commercial operation at the end of October to provide peak shifting services. The total designed capacity of the project is 200 MW/800 MWh, and phase 1 is expected to launch 50% of the designed capacity. Assuming an average household uses 10 kWh a day, the giant battery will have enough storage capacity to supply 80,000 homes

The development of ICB technology started early, but commercialization is still low. ICBs have similar attributes as VRFBs in terms of safety and service life, although the raw materials used in ICBs offer the advantages of lower electrolyte cost and higher cold resistance, and the disadvantage of lower energy density. R&D into ICBs has been slow. Because of poor invertibility of the anode and difficult control of hydrogen evolution reaction, ICB energy efficiency is low, and the backward exchange membrane technology in the past made it difficult to avoid mutual contamination of solutions.

However, with rapid development of the technology in recent years, membrane technology in flow batteries has improved and the use of mixed electrolyte and catalyst has broken through the technical bottlenecks of ICBs. China is in a relatively leading position in this technology globally, with representative companies such as SPIC.

SPIC, a leader in the industry, applied ICB technology in the Ronghe No.1 project to provide energy storage services for the 2022 Winter Olympics in Zhangjiakou region, and successfully provided flow battery solutions for energy storage applications in a low-temperature environment. SPIC owns the independent intellectual property rights of "Ronghe No.1" and announced the start of operation of the mass production line with an annual output of 5,000 units of 30kW “Ronghe No.1” batteries at the beginning of 2022.

Zinc-based flow battery technology is also less commercialized and includes a variety of batteries using zinc as an active substance in negative electrolyte. The raw materials are relatively less costly and nontoxic, but resistance to low temperatures is weak. The biggest obstacles to development are zinc dendrite accumulation and limited surface capacity, which have affected the energy efficiency and service life of the battery, hindering its commercial application in early development.

In recent years, zinc-based flow battery technology has turned toward electrode, membrane material, or battery structure improvement, with successful experiments showing that the formation of zinc dendrites can be reduced and the reversibility of the dissolution reaction of negative electrode deposition can be improved. The commercialization of zinc-based flow batteries is relatively fast in foreign countries, with some companies having launched zinc-based flow battery products, such as Primus Power’s EnergyPod2. However, the industry is still in the R&D stage in China, with representative institutions including the Institute of Metal Research and Dalian Institute of Chemical Physics of Chinese Academy of Sciences.

Similarly, the all-iron flow battery has also been popular in recent years. The positive and negative electrolytes of the battery are separately encapsulated with iron ion solutions of different valence states, so this technology has the advantages of low-cost electrolyte and strong resistance to low temperatures. However, as with ICBs, because of the unsolved issue of severe hydrogen evolution at the electrodes, the commercialization of this technology had been slow.

In recent years, however, several battery manufacturers have managed to break through this bottleneck. ESS, which innovated by storing hydrogen produced by reactions near the electrodes inside the battery system, thus significantly extending battery life, established a grid-scale energy storage project. In addition, Form Energy is a leader in the field and expects to complete the deployment of a megawatt-scale, all-iron flow battery project in 2023. Given the lack of domestic R&D on the all-iron flow battery in China, players in China’s energy storage market should keep a close eye on this trend as the technology develops rapidly.

Although other flow battery technology routes continue to emerge, VRFB is still far ahead in terms of commercialization. The advantages of VRFB are mainly reflected in the maturity of the industrial chain, with major raw materials used in VRFBs, such as electrolyte, ion exchange membrane, and electrodes, having more robust supply chains, and the cost reduction and localization of key components being more advanced. In addition, although VRFB is not dominant in terms of electrolyte cost, considering the innovative input, service life, energy efficiency, and other factors, the full life-cycle cost of VRFB is still lower than that of other technology routes, and this advantage will be difficult to overcome in the short to medium term.

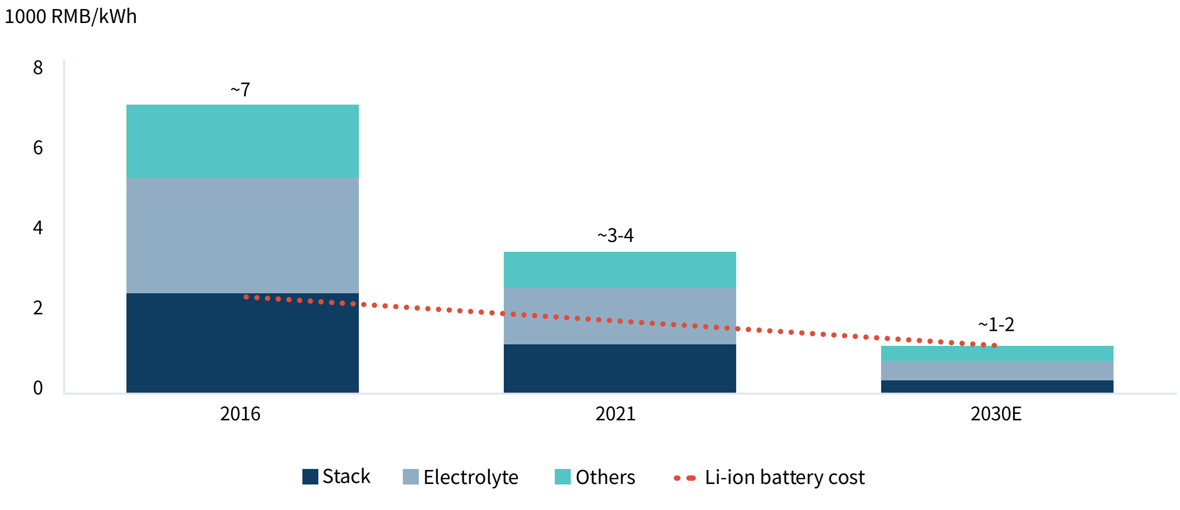
Cost Reduction and Efficiency Improvement Imperative, and Market Guidance Indispensable

The market is optimistic about the future development of flow battery technology, expecting it to gradually replace lead batteries and lithium-ion batteries in the explosive growth of new energy storage applications. Based on the commercialization level of flow battery technology, it is likely that the delivery of flow batteries in the domestic market will be dominated by VRFBs in the short to medium term.

Several investment research institutions have predicted that, by around 2025, China's annual newly installed VRFBs will reach 2.13–3.5 GW. The white paper on the *Development of China's Vanadium Battery Industry (2022)*, released by EVTank, predicted that by 2030, China's accumulated energy storage capacity of VRFBs will reach 24 GW. Huamin Zhang, lead researcher at the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, gave a more positive estimate, saying that the installed capacity of VRFBs will account for 30% of the electrochemical energy storage market, equivalent to about 36 GW, based on the electrochemical energy storage installed at 2030, estimated to be 120 GW. Given that the total installed capacity of flow batteries in 2021 was only about 50 MW, this target means that the market needs to expand hundreds of times.

At present, the cost competitiveness of the flow battery is still at a significant disadvantage. According to TMTPost, the up-front cost of VRFBs in 2021 was higher than RMB 3,000/kWh, more than twice that of lithium-ion batteries. Zheshang Securities predicts that the cost of VRFBs could drop to RMB 2,000/kWh in 5 years and RMB 1,300/kWh in 10 years. Below RMB 2,000/kWh, the up-front cost of VRFBs is expected to reach price parity with lithium-ion batteries (see Exhibit 22).

Exhibit 22: **Predicted reduction of installation cost of VRFB (illustrative)**



RMI Graphic. Source: Literature review, RMI analysis

Considering their longer service life, the full-life cost of ownership of flow batteries will present a significant advantage, but this may not always be true. Because of their high energy density, lithium-ion batteries are mainly used as power batteries in EVs, although a considerable number are recycled for use in energy storage applications on the generation side and grid side through cascade utilization. Due to safety concerns, the state does not encourage recycled lithium-ion batteries to be used in the energy storage industry. However, once a breakthrough is made in the safety of cascade utilization technology, the economy of VRFBs is bound to face greater challenges to compete with recycled lithium-ion batteries, leading to more severe pressure to reduce costs than in the current analysis.

Through the expansion of the cost structure of VRFBs, it can be seen that the main drivers of cost reduction lie in reducing the cost of materials and improving system performance. According to an analysis by the International Renewable Energy Agency, approximately 35% of the up-front cost of VRFBs comes from the stack (primarily the ion exchange membrane), 40% from the vanadium electrolyte, and 25% from the peripherals. Experts from ZH Energy, Shenzhen summarized the drivers of cost reduction in three aspects: improving the stability of the material chemical cycle, reducing the material cost, and improving the overall performance of the system. Current research and innovation efforts by businesses and institutions are focused on improving electrolyte, electrode, and membrane materials to achieve longer service life, cheaper alternative materials, and more efficient reaction performance.

At the same time, exploration of alternative electrolyte selection in flow batteries is also a major innovation direction. As mentioned above, except for VRFBs, technical routes such as zinc-based, ICBs, and all-iron flow batteries all have the advantage of lower electrolyte cost with more potential in cost reduction. With the breakthrough of battery engineering technology, the reaction efficiency and material stability of these batteries will be significantly improved, showing possibility for them to surpass VRFBs to become the most mainstream technology routes in the future.

In addition, current mainstream electrolytes are small molecular solutions of metals and inorganic substances, so the isolation and conductivity of electrolyte ion exchange membrane must be high, resulting in the high cost of the stack. Some research institutions are trying to use macromolecular organic solution as electrolyte to reduce the cost of the membrane and the use of precious metals, and to simplify the use of the membrane by looking for immiscible electrolyte or solid electrolyte to achieve a natural isolation effect. However, these routes are still in the experimental research stage, and there are no products robust enough to compete with VRFBs. But in the medium to long term, players in flow battery industry will need to pay close attention to the challenges posed by changing technological paths and the development of alternative technologies.

There are indeed a variety of demand applications that support an optimistic outlook for flow batteries, but the flow battery industry still faces many challenges to achieve the target of hundreds of times of growth. Therefore, policy guidance will be necessary to promote development of the industry. Only by boosting market confidence and scale can we better promote process improvement and cost reduction, enabling flow batteries to catch up with other energy storage technologies economically and achieve a breakthrough in market share. Policymakers could consider the following aspects for guiding the development of the flow battery market:

- For areas with limited access to pumped storage (such as the arid region in Northwest China), power generators should be encouraged to prioritize flow batteries for new energy storage equipment used for enhancing grid connection of renewables and providing ancillary services in the future.

- Areas with high fire safety requirements (such as dry and windy climate areas, densely forested areas, and densely populated urban areas) should have guidance in choosing flow batteries in energy storage facilities deployment.

- Regulatory enforcement of the recycling and use of energy storage batteries should be strengthened to prevent the recycling of substandard electrochemical batteries (such as lead batteries and lithium-ion batteries) from competing with flow batteries by releasing negative externalities to control costs.

Qiyu Liu, Guangyu Tan, Guangxu Wang et al., *Prospects for China's Next-Generation Clean Low-Carbon Technologies,* 2023, https://rmi.org/insight/prospects-for-chinas-next-generation-clean-low-carbon-technologies/.

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