Sweden-China Bridge

Collaborative Academic Platform for the
Electrification of Transportation Systems

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ELECTRIFICATION OF THE TRANSPORTATION SYSTEM IN CHINA

EXPLORING BATTERY TECHNOLOGY FOR ELECTRICAL VEHICLES IN CHINA 1.0

Title: Exploring Battery Technology For Electrical Vehicles In China 1.0.

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ABOUT THE SWEDEN-CHINA BRIDGE PROJECT

This project funded by The Swedish Trafikverket (TRV), formally started the 1st of September 2020, and will last until the end of 2022.

Exploratory approach

This project is exploratory in nature and includes a step-by-step approach to knowledge development in the Swedish and the Chinese context. The project spans different areas of knowledge in which we will highlight what technologies and systems are prioritized in China, Sweden and in Europe, what drivers and motives exists for them, what actors are involved in the transition to electrified, intelligent and integrated transport systems, and what conditions and business models look like to achieve this conversion to electrified and integrated transport systems in an intelligent and smart society.

The purposes of the Sweden-China Bridge Project

1. The project aims to establish and develop an academic knowledge-sharing and -transfer platform between Sweden and China for collaboration between universities and research institutes in the two countries, in order to contribute to increased understanding and information and knowledge sharing on the technical and commercial development of electrified vehicle systems, integrated transport system solutions, and energy supply infrastructure as a fully integrated system of intelligent and smart cities.

2. From this perspective, the project will explore the development and implementation of relevant technology for the electrification of vehicles, such as fuel cells, bioenergy, battery storage, combinations of energy systems for hybrid vehicles, energy supply for integrated electrified vehicles, integrated electric road technology, associated charging infrastructure, and static and dynamic technology.

3. We also intend to explore the management of renewable energy supply systems, from the production of renewable electricity to its distribution to consumers of electrified transport systems, which is needed to ensure that electrified vehicles and transport systems.

Expected value creation

1. To create insights into the current and future status of electrification of transportation systems in Sweden and in China from technical, social, societal and economic perspectives.

2. To learn and mutually develop insights into how new knowledge, technology, system-based solutions, logistics and transportation systems can be developed, commercialized and operated according to a life cycle perspective in both Sweden and China.

3. To create a long-term learning context in which Sweden and China exchange experience for the benefit of both countries and their industries.

4. To develop a deeper understanding of how Sweden and China are managing the large-scale electrification of the road network using different technologies, including electric charging, energy production (fuel cells, hybrid vehicles, battery storage and electric roads): what do the short- and long-term potentials look like? How are they using long-term industry policy instruments to develop technology and implement it in society? How are they outlining business models for the large-scale roll-out of electrified transportation systems?

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A special appreciation is directed to our Shanghai research team, Mr. Ran Dong, Mr. Xiang Chen, Mr. Sheng-dong Zu, and Professor Susan Lijiang Sun, for working with us in the exploration of technology development in key areas of battery, hydrogen and inductive charging. Thank you for your valuable contribution to our under-standing of the development in China.

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As project leader I am grateful to my research fellows and colleagues in this project, Dr. Jasmine Lihua Liu, Ran Dong, Professor Tomas Müllern, Tech.lic. Arne Nåbo, and Dr. Philip Almestrand-Linné.

I thank all of you from the bottom of my heart.

Professor Mike Danilovic on the behalf of the entire research team.

ABSTRACT

Batteries is one of the main systems of electric vehicle. Batteries determine the total performance and define the capabilities of the electric vehicle regardless it is a passenger vehicle or heavy truck. Batteries are also determining the total price of the electric vehicle to large extend. In our first two reports on battery-swapping, Exploring Battery-Swapping For Electric Vehicles in China 1.0, and Exploring Battery-Swapping for Heavy Trucks in China 1.0, our focus was on passengers' vehicles, and heavy trucks and the development and establishment of large-scale battery-swapping systems in the Chinese context.

Due to the importance of batteries for the performance of electric vehicles, it is important to explore and understand the development of technologies for batteries in China as China is not only largest manufacturer of electric vehicles but also one of the largest developers and manufacturers of batteries used in electric vehicles.

In this report we are focusing on the technology development in historic perspective of the last 15 years in China. We see that the lithium-ion technology is the dominant technology, but we also see new emerging battery technologies that might be the game changer for the performance of electric vehicles. We demonstrate the dynamics of main battery technologies, LFP (lithium iron manganese, LiFeO4, battery cell) battery and NMC (lithium nickel manganese cobalt oxide battery cell) battery, the distribution of installed volumes between LFP and NMC in the Chinese market. During the early days of modern battery, the LFP battery technology were dominant with 69% of the market while NMC had 27% of the market. Over the last 5 years we can see big change where NMC is moving to the 67% level and LFP is going down to 32%. During the emerging stage of the China's new energy vehicle development, LFP batteries account for 69-72% of the installed capacity due to their low cost and mature technology.

With the introduction of NMC batteries into the market, their energy density, capacity and operational vehicle range and safety performance have been improved compared with LFP batteries. In recent years, the installed capacity of NMC battery technology accounts for two-thirds of the market in China. With the intensification of competition in the new energy vehicle market, NMC batteries with higher energy density and better cost efficiency ratio have become the new favorite and are still the mainstream of the market until now.

The CTP (cell to pack) technology of CATL (Contemporary Amperex Technology Co., Limited) improves the energy density and group efficiency of NMC battery, and the blade battery developed by BYD improves the energy density and safety performance based on the low cost of LFP battery. LFP battery market share expected to grow.

However, professionals in the industry point out that the energy density of LFP battery and NMC battery is close to the theoretical limit, the energy density limit of high nickel material + silicon carbon negative cell is about 300Wh/Kg At current time only CATL and GOTION High-Tech have reached this level.

New battery technologies are emerging, such as the Li-S (Lithium-Sulfur) battery that was first proposed in the 1960s, but progress has been slow so far; it was not until the 21st century that China's research on Li-S batteries began gradually to develop. Solid-state lithium and lithium-rich manganese-based battery technologies are becoming the new hot-spots of battery development in China.

Beside capacity and performance, the main challenges for battery development that we have identified are:

- Safety issues, especially the risk of fire during battery charging.
- The need to improve battery-management systems in collaborative settings between vehicle OEMs and key partners such as battery manufacturers and battery swapping technology developers.
- The management of batteries in their second and third lifecycles, as well as the decommissioning and recycling of old batteries.

According to the development of the existing market, the market size of power lithium battery pack recycling will reach about 6.5 billion yuan by 2020, of which the market size of ladder utilization is about 4.1 billion yuan, and the market size of recycling is 2.4 billion yuan. By 2023, the total market size for battery decommissioning will reach 15 billion yuan, of which the market size of ladder utilization is about 5.7 billion yuan, and the market size of recycling is about 9.3 billion yuan.

Key words: Electric vehicle batteries, battery technology, electric vehicle, Electric vehicle in China, battery development in China.

OUTLINE OF THE PAPER

This paper consists of six main parts:

Part one
Introduction to battery development in China

In the 1st part we draw the historical line of the battery development in China the last 15 years and relate it to the global development of electric vehicles and battery technologies. Specially we describe the logic of price development for batteries compared to the situation of semiconductors and microprocessors.

Here we also describe the major trends in the Chinese battery technology development from 2015 to 2020.

Part two
Standards And Policies For Batteries In China

In this part we describe the dominant standards and policies for the fast development of battery technologies in china in the period between 2006-2020.

We identify the main phases in the development of policies and discuss the implications for the R&D of battery technologies in China.

Part three
Development of battery technology in China

In this part we identify the main research entities in Chinese academics, industry and discuss the main technological development trends in China in the battery domain.

Part four
TRL estimation of Chinese battery technology

In this part we analyze the identified battery technologies according to the Technology Readiness Level analysis developed by NASA in the 1960s. We demonstrate how different technologies are following each other and estimate the next generation of battery technologies in China.

Part five
Analysis

In this part we are analyzing the technological development and identify the main routes of new battery technologies in the Chinese context and discuss some identified challenges in the development.

Part six
Conclusions

This part is outlining main conclusions regarding the battery technology being developed in China.

RESEARCH METHODOLOGY

The research in the Sweden-China Bridge project is based on primary data from company visits, observations, interviews and through the collection of secondary data in English and in Chinese. One senior research team member, Dr. Jasmine Lihua Liu, is of Chinese origin and thus we were able to cover this area from Chinese perspectives, both in respect of a literature search and from the point of view of a deeper understanding of the societal, cultural, and contextual environment in the process of electrification of transportation in China. We followed discussions in different webinars, conferences, and discussions among experts to deepen our understanding.

Dr. Liu is an experienced researcher both in the Swedish and Chinese context of transformation towards renewable energy. She received her PhD in Innovation Sciences from Halmstad University in 2019 and thus is well oriented in the Swedish context. Mr. Ran Dong is a researcher at Shanghai Dianji University and member of a local research team consisting of Mr. Ran Dong, Mr. Xiang Chen, and Mr. Shengdong Zu, under the lead of Professor Susan Lijiang Sun. The research underling this report is undertaken in 2020 as desktop-based research in the Chinese context. Mr. Ran Dong has been the main data collector and the main co-author of this report.

In October – December 2020 part of the research team travelled to China where they visited both corporate organizations, leading institutions, and leading academic institutes in Beijing, Shanghai and Shenzhen, and carried out observations and personal interviews with people in the research area of the electrification of transport systems in China.

During December 2020, in one intensive week, we conducted company visits, discussions and formal interviews with key players in the electrification of Shenzhen city in southern China. This working week was a joint collaborative venture with the Scania China Innovation Team in Beijing. The information collected during this intensive period in China is due to be elaborated in forthcoming papers on electrification technology development and research into the electrification of Shenzhen as the only city in the world that has succeeded in achieving 100% electric taxis, buses and most of the intra-city-based logistics and working vehicles.

In May 2021 we collaborated with Scania china Innovation Team in joint exploration by corporate visits several Chinese battery-swapping developers and operators in order to explore the role of battery-swapping for heavy vehicles such as trucks.

In April-June 2021 we conducted several seminars in Sweden with participants from academia and industry to share our observations and listen to questions that were raised by academics and practitioners on electrification of transport in China in general and on battery-swapping. This dynamics in our research is a way to create awareness and mutual learning based on our ongoing research on electrification of transport in the Chinese context.

PART ONE
INTRODUCTION TO BATTERY DEVELOPMENT IN CHINA

In recent years, new-energy electric vehicles with high energy efficiency, low noise and zero tail-pipe emission have attracted wide attention from countries all over the world. China's new-energy electric vehicle industry started in the early 21st century. In 2001, the research project of new energy vehicles was listed in the national "863" major scientific and technological subject during the tenth five-year plan period, and the strategy of taking gasoline vehicles as the starting point and advancing towards the goal of battery-based and hydrogen vehicles was planned. Since the eleventh five-year plan, China has put forward the strategy of "energy saving and new energy vehicles", and the Chinese government attaches great importance to the research, development, and industrialization of new energy vehicles and related technologies such as batteries.

Finally, based on the contemporary mature technology of pure electric vehicles, the old internal combustion technology engines (ICE) based on carbon-based fuel, are gradually being replaced. The modern hybrid electric vehicles (ICE combined with battery energy) are also being phased out by pure electric vehicles. The new energy vehicles becoming the dominant direction of development, as we can seen it now in China, are the battery-based and hydrogen-based vehicles.

In 2019, 2,21 million pure electric and plug-in hybrid vehicles were sold worldwide, up 10% from a year earlier. Pure electric vehicles accounted for 74% of the total. The production and sales of pure electric passenger vehicles in China both increased to about 70%, and pure electric passenger vehicles became the mainstream of the production and sales of new energy vehicles [1]. As one of the technical cores of pure electric vehicles, battery is the most critical power source and energy storage of pure electric vehicles. In terms of user experiences, it determines the performance of the vehicle, the operational range and safety performance of pure electric vehicles. The battery technology and battery design also determines the total price of the vehicle as battery often is on the level of 40-60% of the total vehicle price. And in terms of production and marketing, it determines also the production cost and sales price of battery and new energy vehicles.

Since the 1990s, lithium-ion battery has become one of the most used battery technologies with the most efficient comprehensive performance due to its advantages of combined light weight, good cycle life and high energy density and the total price. Constrained by materials and manufacturing processes, the development of power batteries is faced with the challenge of reducing production costs, increasing energy density, and improving safety performance as well as battery design to fit into different vehicle architecture regardless it is the most common fully integrated system of vehicle and battery or utilizing the battery-swapping system. In the current fast development global environment of new energy vehicles, power batteries have received full attention in china as well globally. Relevant automobile and battery manufacturing enterprises are constantly exploring the use of new materials and technologies to improve the performance and capabilities of existing batteries, and the research and development of new batteries has become a major focus in the field of new energy vehicles.

The development of China's new energy vehicles market

Before 2009, China had been exploring a way to realize the leapfrog development of the traditional ICE-based automobile industry, and finally decided to switch to technologies based on electrified vehicles and to develop the technology and complete systems of new energy vehicles to support decarbonization in order to improve the environment.

From 2009 to 2012, with the establishment of the development strategy of electric vehicles, the Chinese government introduced pilot projects of new energy vehicles in a large scale in many cities across the country through R&D investment and direct subsidies and gave priority to their deployment in the public sector. In the next five years, 2013-2017, China's electric vehicle industry and market were developing rapidly, driven by a combination of air quality, energy security and automotive industry revitalization goals.

Development history of electric vehicles in China

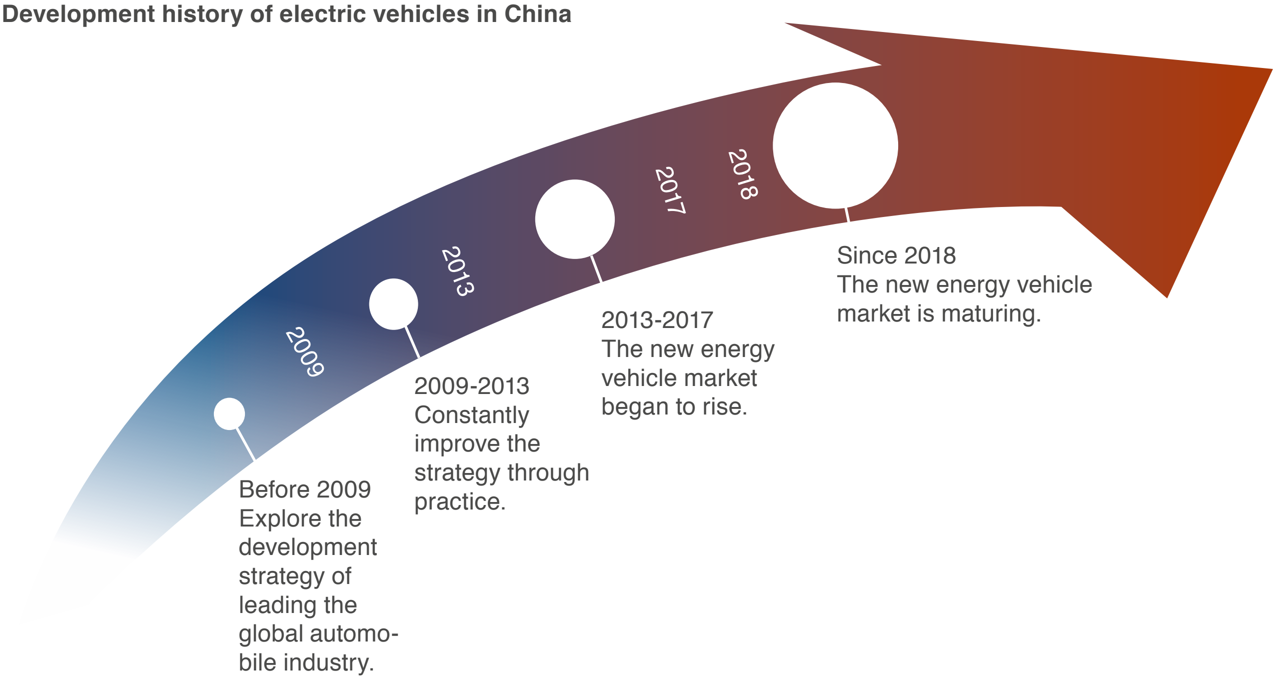

Figure 1: Development history of electric vehicles in China
Source: International Council on Clean Transportation (ICCT) & China EV100[2], 2021

Figure 1 illustrates the four main stages of new energy vehicles (NEV) development in China.

After 2018, China has gradually shifted from a relatively single stage of industry subsidies to a model that combines incentives with regulations and standards to further unleash market potential. This policy shift, along with a more open competitive landscape, is a sign of China's growing confidence in its electric vehicle strategy and a maturing electric vehicle market.[2]

By 2019, Chinese electric vehicle development has gone through a rapid development decade, starting from the iconic "1,000 vehicles in 10 cities" project. Over the past decade, China has rapidly grown into the world's largest market for electric vehicles, accounting for half of global sales of electric passenger cars and more than 90 percent of sales of electric buses and trucks.

Today in 2020 China has more than 100 domestic brands developing and manufacturing pure electric vehicles, passenger cars, trucks and buses and some cities has introduced full scale of electrified transport solutions such as the city of Shenzhen.

The development of battery technology in China

Technology in general, and technology development, can be seen from a metaphorical life-cycle perspective, as a cyclic and dynamic development from idea to maturity and final decline, before ending in the technology graveyard. Technology has a life cycle, like any other living things. All technologies are facing decline and are overrun by new technologies. The only question is the time it takes for one technology to be overtaken by the other. The life cycle of technology can vary, and the speed of development can be different for each technology domain and generation.

Semiconductor prices are falling

We are used to see technology development of semiconductors as escalating according to the Gordon Moore ideas, the Moore Law, stressing that:

> *Gordon Moore's 1965 forecast that the number of components on an integrated circuit would double every year until it reached an astonishing 65,000 by 1975 is the greatest technological prediction of the last half-century. When it proved correct in 1975, he revised what has become known as Moore's Law to a doubling of transistors on a chip every two years. Since then, his prediction has defined the trajectory of technology and, in many ways, of progress itself [3].*
>
> (Rotman, 2020)

Moore's argument was rooted in economic reflection and the economic consequences of rapidly declining prices as volumes increases. But like for all living things, also the logic of the Moors Laws might come to the flattering of the curve in what from the beginning looked like never-ending escalation of volumes and likewise never-ending lowering of prices.

> *The newest Intel fabrication plant, meant to build chips with minimum feature sizes of 10 nanometers, was much delayed, delivering chips in 2019, five years after the previous generation of chips with 14-nanometer features. Moore's Law, Leiserson says, was always about the rate of progress, and "we're no longer on that rate." Numerous other prominent computer scientists have also declared Moore's Law dead in recent years. In early 2019, the CEO of the large chipmaker Nvidia.* (Rotman, 2020)

The cost of a chip's fabrication is rising at around 13% a year and is expected to reach $16 billion or more by 2022. Not coincidentally, the number of companies with plans to make the next generation of chips has now shrunk to only three, down from eight in 2010 and 25 in 2002.

Batteries are not semiconductors

What was relevant in semiconductors and microprocessors seams not to be relevant for battery development. Already in 1920s T.P. Wright outlined the basic ideas of the Wright's Law.

> *The law is also a bright oncoming locomotive bearing down on the gasoline-powered vehicle industry. As long as cost parity — expected in 2023 or 2024 — leads to a nascent mass EV market, the embryonic industry will rapidly go on to further price declines as its cumulative production doubles and doubles again. As for the already-humongous conventional auto industry, at current sales rates, it will have to wait about 29 years to double the fleet, according to Sam Korus, an analyst with ARK Invest. [3]*
>
> (Rotman, 2020)

> *"Actually, the 1965 Moore's Law seems to be a special case of Wright's Law, spelled out by Theodore P. Wright in a 1936 paper, 'Factors affecting the costs of airplanes.' In fact, Wright's Law seems to describe technological evolution a bit better than Moore's—not just in electronics, but in dozens of industries." [4]* (McCormick, 2012)

> *"When we are looking at disruptive technologies, we are looking at technologies experiencing a w and sectors, and that can serve for further innovation. Batteries fit that, and Wright's Law has been the key element to finding the cost decline.*
>
> *As an example, from 2010 to 2015, lithium-ion battery capacity doubled seven times, from 0.48 gigawatt-hours to 62 GWh. The average price of batteries at the pack level plunged from $1,194 per kilowatt hour to $384. Strictly speaking, the 18% rule should have taken prices down to about $261 ($384 is about what Wright's Law calls for with six doublings). But it was still a roughly two-thirds plummet.*
>
> *From 2015 to 2020, battery capacity grew 2.7 times and the price again plunged by two-thirds, to an average of $137/kWh. That overshot the 18% rule, by which the price should have*

dropped only to about $213/kWh. But if you had strictly tracked the 18% rule from 2010 to 2020, the price ended up right around where it should have been.

Following Wright, battery prices should drop to $84 per kWh in 2025, well below the holy grail milestone of $100/kWh. In 2030, they should be an astonishing $58/kWh, and $45 in 2035. The price movements in the 2030s seem dramatic, but they are less so than the prior two decades, namely because it will be harder and harder to double total capacity.

In addition, moving from the currently popular NMC cathode to one with just 0.5% of both cobalt and manganese, and 90% nickel, should reduce raw material costs by about a fifth while increasing energy density by almost a quarter, he said"[3] (Rotman, 2020)

For years we have faced slow development in the battery technology domain. However, as the electrification of transport and rapidly uprising numbers of electric vehicles so has the interest for new battery technology been uprising, its performance has improved, and prices has fallen. The R&D of batteries has succeeded to deliver new battery technologies, although not at the same speed and price reduction as semiconductors and microprocessors. Batteries follow rather the Wright law. We need to understand that different technologies have different patterns of development and different logic.

Prices of electric vehicles in parity with ICE by 2025

It is expected that by 2025 the prices of electric vehicles will be in parity with prices of combustion (ICE) vehicles. After 2025 the prices on electric vehicles are expected to go down for several reasons. Scale of economy in general, decline in battery prices due to technology advancements and manufacturing scale of economy, increased competition, simpler and cheaper battery and vehicle design, and lower manufacturing cost for electrical vehicles. In general, electric vehicles are cheaper than ICE base vehicles, simpler with fewer systems and components and need less employees to manufacture and assembly electric vehicles.

As the batteries are dramatically moving in the value chain of vehicles, from being the starter of combustion engines to become the main system of an electric vehicle, batteries are becoming crucial to the overall development of electric vehicles.
For this reason, it is important that explore and understand the status of the battery development in China

Batteries are becoming strategic issue

Batteries for electric vehicles has very similar function as the role of otto-engines (ICE) has for fossil-based vehicles. Battery is the heart of a modern electric vehicle, together with the battery-management software system. Batteries determine the performance, the total price of new and second-hand price of vehicles, and determine the life cycle of an electric vehicle, to large extend. Batteries are also one of the main concerns of consumers purchasing the electric vehicle.

Also, politicly the access to material to manufacturing of batteries and manufacturing of vehicles as system has become politicly sensitive all over the world, as the importance of electric vehicle rapidly is increasing, and geopolitics is obvious. Now in 2021 we see that some powers are struggling to establish self-proficiency in development and manufacturing of batteries for electric vehicles.

In European Union (EU) new strategies are evolving to support establishing manufacturing plants for batteries all over the EU.

Figure 2:
Volkswagen integrated MEB-electric car platform
Source: Holms[5]*, 2019*

Batteries are also a strategic system in electric vehicles that make the branding difference to other brands.

Volkswagen is one European brand that is taking the European lead in the development of electric vehicles. The idea of Volkswagen is to design a basic module that can be sold as system to other vehicle manufacturers, and they can bult their electric vehicles on Volkswagen platform. This way the scale of economy could be improved while the individual company control of their own technology is more limited.

Contemporary status of battery technology development in China

The contemporary dynamics of battery technologies in China

At present in 2020, the main types of batteries for electric vehicles in China are NMC batteries and LFP batteries. The technologies are relatively mature and large-scale production has been realized.

Figure 3 shows the dynamics of installed battery technologies, battery capacity and the ratio of LFP battery and NMC battery in recent 7 years, 2015-2021. Notice that the data in 2021 presented is only covering the first half of 2021.

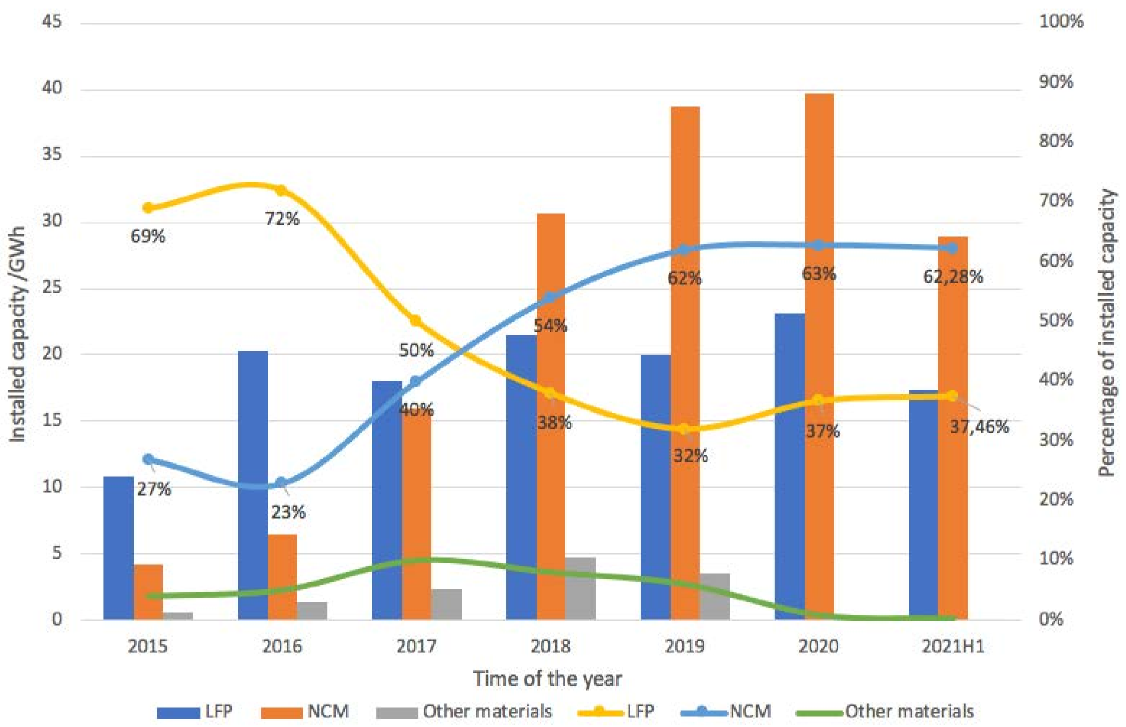

Figure 3: The installed capacity of LFP battery and NMC battery in China in recent 6 years. Figure created by Ran Dong
LFP: lithium iron phosphate battery
NMC: lithium nickel manganese cobalt oxide battery
Source: www.d1EV.com[6-7], GaoGong Industry Research Institute (GGII) [8-10], ZhiYan.org(www.ibaogao.com)[11]

Figure 3 shows the dynamics of main battery technologies, LFP battery and NMC battery, the distribution of installed volumes between LFP and NMC in the Chinese market. During the early days of modern battery, the LFP battery technology were dominant with 69% of the market while NMC had 27% of the market. Over the last 5 years we can see big change where NMC is moving to the 62,28% level and LFP is going down to 37,46%. During the emerging stage of the China's new energy vehicle development, LFP batteries account for 69-72% of the installed capacity due to their low cost and mature technology. With the introduction of NMC batteries into the market, their energy density, capacity and operational vehicle range and safety performance have been improved compared with LFP batteries.

Blade battery enters the market

In 2020, the Chinese vehicle developer and manufacturer BYD, successfully developed a new battery technology and put it on the market, the blade battery. The blade battery is a significant technical improvement of the traditional LFP battery.

Based on lower cost of the new blade battery technology, compared to NMC battery, and the performance in terms of the energy density, capacity, operational performance, and safety performance of the new blade battery technology, and its installation volume has shown an increasing trend.

This development of technologies is based on demands from the industry using batteries in the development of vehicles but also supported by different policies and standards in China.

In the following sections we will explore the Chinese policies and standards that have been important in the development of battery technologies.

PART TWO
STANDARDS AND POLICIES FOR BATTERIES IN CHINA

China's standards for batteries

With the rapid development of new energy vehicles in China, the development of power batteries as core component of the vehicle is also following the overall trend of new energy vehicles.

However, in the early development of battery technology, the power battery-related standards were based on one single standard. In those early days, only the industry standard QC/T743-2006 was in place as a reference. The lack of authority for standard development, and extensive, industry supervision and development of technology and standards were not clear. China's electric vehicle industry and power battery industry must meet the newly developed and current industry norms and regulatory standards [12].

Regarding power batteries for electric vehicles, the General Administration of Quality Supervision, Inspection and Quarantine of China (AQSIQ) and the Standardization Administration of China jointly issued six national standards on May 15, 2015, which will be fully implemented in 2016.

With the continuous expansion, growth and the increased market scale of electric vehicles, and the gradual improvement of the energy density and installed capacity of power batteries, battery safety problems occur from time to time. In 2020, several relevant standards have been revised[13]. **Table 1** summarizes and compares Chinese and international standards on power batteries.

CHINA STANDARD			THE INTERNATIONAL STANDARD		
Standard number	**The name of the standard**	**Date of implementation**	**Standard number**	**The name of the standard**	**Date of implementation**
GB/T 31467.1-2015	Lithium-ion battery packs and systems for electric vehicles – **Part 1:** Test procedures for high power applications.	2015-05-15	**ISO 12405-4:2018**	Electrically propelled road vehicles —Test specification for lithium-ion traction battery packs and systems. **Part 4:** Performance testing.	2018-07
GB/T 31467.2-2015	Lithium-ion battery packs and systems for electric vehicles – **Part 2:** Test procedures for high energy applications.	2015-05-15			
GB/T 31467.3-2015	Lithium-ion battery packs and systems for electric vehicles – **Part 3:** Safety requirements and test methods.	2015-05-15	**ISO 12405-3:2014**	Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems . **Part 3:** Safety performance requirements.	2014-05
GB/T 31484-2015	Cycle life requirements and test methods for power batteries for electric vehicles.	2015-05-15			
GB/T 33598-2017	Specification for recycling and disassembly of vehicle power batteries.	2017-05-12			
GB/T 34013-2017	Specifications and dimensions of power batteries for electric vehicles.	2018-02-01			
GB/T 38661-2020	Technical conditions of battery management system for electric vehicles.	2020-10-01			
GB 38031-2020	Safety requirements for power storage batteries for electric vehicles.	2021-01-01	**ISO 6469-1:2019**	Electrically propelled road vehicles — Safety specifications. **Part 1:** Rechargeable energy storage system (RESS).	2019-04

Table 1: Chinese standards for batteries contrast with international standards
Source: www.gov.cn[14-21], International Organization for Standardization (ISO) [22-24]

As can be seen from the standard comparison **Table 1**, China has been closely following the world standards and developing various domestic standards related to the standards in the west regarding batteries.

In addition to developing standards for the battery itself, there are also a series of standards for battery-related components and systems, such as BMS (battery management system), that is not covered in this paper.

The main content of the standards

The above-mentioned national standards, **Table 1**, mainly involve technical parameters such as electricity performance, life cycle, safety, interchangeability, recycling and so on.

Electrical performance aspects include electrical performance requirements and experimental methods, high power, and high energy test procedures. In the standard GB/T 31467.1-2015 and the standard GB/T 31467.2-2015, mainly for the basic performance test, including energy and capacity test, power and internal resistance test, no load capacity loss, etc.

In the life test, file GB/T 31484-2015 provides that in addition to the standard life test, it also involves the cycle life under working/operational conditions.

Safety includes the standard GB/T 31467.3-2015 and GB 38031-2020. In addition to stipulating the safety requirements and test methods for power batteries, the standard has also changed the range of battery types from the original lithium-ion battery to various power battery technologies. The sample level increases the system level based on the cell and module; The new standard default charging-discharging rate is 1 Coulomb, which requires more stringent requirements. The experimental conditions also clearly specified the room temperature, ambient temperature, relative humidity, air pressure and other factors.

- In terms of interchangeability, the standard GB/T 34013-2017 covers dimensions, specifications, and codes, etc.
- In terms of recycling, the standard GB/T 33598-2017 has made corresponding specifications for the recycling of power batteries.
- In addition, there are also specifications and standards for BMS (battery management system), however not covered in this report.

Meaning of the implementation of the standard

The implementation and use of the existing national standards provide a unified measurement and testing standard for the development of Chinese domestic power battery industry and provide an effective supervisory basis for the regulatory authorities. The current standards have basically covered the whole process of power batteries from development, production to decommissioning and recycling.

The interconnection and combination of different standards cover all levels of components such as power batteries, modules, and systems, which is conducive to the healthy development of power battery technology and the related battery and vehicle industry. However, the existing national standards refer more to the existing foreign standard systems at the module and system level. Its advantage lies in the rich and mature experience in the development and application of international standards, which plays an important guiding role in the development of standards in China. On the other hand, the formulation and continuous improvement of the standard also reflects the booming development of domestic power battery. The standards development in China is related to the international standards, but as the Chinese development of batteries are taking a leading role in the development of electric vehicles, so is the development of Chinese standards taking a global leading position to which other international standards and standardization institutions need to adopt. The global development is gradually adopting to the speed of technology development in China as well as globally.

Background to the release of the new battery policy

Near the point of decline in financial subsidies, the entire power battery industry is in a state of upheaval change in 2019. Financial subsidies have fallen sharply, the power battery industry door opened to the outside world, ”whitelist” of technologies and products has become a history, the rapid emergence of new energy vehicles, the power battery safety inspection and testing round after round, the Chinese domestic new energy vehicle domain is no longer new. It has grown and matured, as well as the regulatory and policy shaping actors. To stabilize the electric vehicle market and promote the development of power batteries, the Chinese government has issued a series of relevant policies.

The content of the new policy

Table 2 lists four new policies that have a significant impact on Chinese domestic power batteries being implemented in the last five years. The release of the policy mainly revolves around the marketing of power batteries and new energy vehicles, product safety and other issues.

Number	The name of the policy	The agency	Keywords	The release date
1	Action plan to promote the development of automotive power battery industry.	Ministry of Industry and Information Technology, Development and Reform Commission, Ministry of Science and Technology, Ministry of Finance.	Power battery, product performance, quality and cost, new energy vehicle promotion and application.	February 20, 2017
2	Notice on further improving the policy of financial subsidies for the promotion and application of new energy vehicles.	Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology, Development and Reform Commission.	Subsidy policies and subsidies will decline in 2019.	March 26, 2019
3	Effectively strengthen the safety supervision of new energy vehicles, and carry out the investigation of potential safety hazards.	The Ministry of Industry and Information Technology in collaboration with the Industrial Development Center	New energy vehicle safety, power battery safety.	June 17, 2019
4	New Energy Vehicle Industry Development Plan (2021-2035).	General Office of the State Council.	New energy vehicle 2035, power battery, hydrogen fuel cell.	November 2, 2020

Table 2: Policy on power batteries
Source: www.gov.cn [25-27]

1. The point of the first policy:

- By 2020, product performance will be greatly improved. The specific energy of the new lithium -ion battery unit exceeds 300 Wh/kg. The specific energy of the system strives to reach 260 watt-hour/kg and reduce the cost to less than 1 yuan/watt-hour.
- Product safety meets the needs of large-scale use.
- Rational and orderly development of industrial scale. The total production capacity of the power battery industry exceeds 100 gigawatt-hours (GWh), forming a leading enterprise with international competitiveness whose production and sales scale is above 40 gigawatt-hours.
- Major breakthroughs have been made in key materials and components. Key materials and components such as anode and cathode, diaphragm and electrolyte have reached the international first-class level.
- High-end equipment to support industrial development. Power battery research and development, manufacturing, testing and verification, recycling and other equipment to achieve automatic and intelligent development, production efficiency and quality control level significantly improved, manufacturing costs significantly reduced[25].

2. The point of the second policy:

- The subsidy amount will drop by more than 50% from the 2018 level.
- There is no subsidy if the energy density of passenger car power battery system is lower than 125 Wh/kg.
- The subsidy will be cancelled for electric passenger cars with a range of 250 km and passenger cars with a range of less than 200 km.
- Canceling land subsidies and turning them into subsidized charging infrastructure.
- No incentive coefficient will be set for vehicles with system energy density above 160 Wh/kg, and the subsidy will be doubled[26].

3. The point of the third policy:

- Strengthen the vehicle operation monitoring system.
- Strengthen the safety supervision of new energy vehicles.
- Improve the safety standard and specification system.
- Strengthens the profession selfdiscipline, completes the publicity guidance.

4. The fourth plan focuses on six areas:

- Improving technological innovation capacity.
- Building a new industrial ecosystem.
- Promoting integrated industrial development.
- Improving the infrastructure system.
- Deepening openness and cooperation, and
- Ensuring measures[27].

Policy sets out a vision for 2025

By 2025, the market competitiveness of China's new energy vehicles will be significantly enhanced. Major breakthroughs were made in key technologies such as power batteries, driving motors and automobile operating systems. Security has been improved across the technology domains. The average energy consumption of the new pure electric passenger cars shall be reduced to 12.0 KWH/100km.

The sales of new energy vehicles have reached about 20% of the total sales of new cars. Highly autonomous vehicles have been commercialized in limited areas and under certain circumstances, and the convenience of charging has been significantly improved[10].

2.2.3 Implications of new policy implementation

"Action plan" to promote the development of auto power battery industry to develop and release, scientific planning of the automobile power battery industry development goals, further clear tasks and measures, to accelerate the raise the level of power battery products performance and quality, improve the industry development of our country's core competitiveness, promote the sustainable development of new energy automotive industry.

Since June 25, 2019, when the transitional period of new energy vehicle subsidy policy ended, the production and sales of new energy vehicles have experienced five consecutive drops. The cost of manufacturing of new energy vehicles has risen significantly. For hybrid vehicles it is too large extend a consequence of developing and manufacturing dual technology systems, ICE and electric power trains, that increase significantly the development and manufacturing cost.

Technological innovation in all domains of the industrial value chain has not been able to reduce costs as fast as the decline of government subsidies in the Chinese context. Industrial development has slowed down. In turn, a series of reactions have occurred, resulting in accelerated industrial chain reshuffle such as new energy vehicles, power batteries and lithium battery equipment, and the survival of the fittest industry has come earlier than expected. The rapid growth of the Chinese electric vehicle industry has been rapid and thus created extensive demand on needed technologies, components and skilled and talented people. All together the prices on electric vehicles are both reduced in certain areas as well as increased on the total system level.

As a guiding policy document for the development of China's new energy automobile industry in the next 15 years, The New Energy Automobile Industry Development Plan (2021-2035) plays an important role in China's future development of new energy automobiles. It involves several technologies such as battery-swapping, power cells and batteries, hydrogen fuel energy and other proposals, which will play an important role in guiding the development of the entire vehicle and transport industry.

PART THREE
DEVELOPMENT OF BATTERY TECHNOLOGY IN CHINA

Development of batteries in China is mainly conducted by university teams and industry-based R&D focusing on chemistry and material perspectives.

In the following sections we intend to identify main actors and focus that they have focused on until now.

Chinese university

China's research institutes and universities are actively exploring the study of power battery positive materials, as shown in **Table 3.**

From several studies listed in Table 3, research on positive pole materials has focused on chemical structures and new compounds.

Number	Research team	The content and results of the study	Time period
1	Zhang Xinbo, Institute of Applied Chemistry, President of the Chinese Academy of Sciences.	New technologies for the integration of solid-state lithium-air batteries from material matching to prototype devices. The research results initially solve the core scientific problems of realizing solid-state lithium-air batteries, and successfully demonstrate the feasibility of solid-state lithium-air batteries. The reversible charging and discharging of solid-state lithium air battery has been realized, The energy density of liquid lithium air battery developed by the team has reached 780Wh/kg.	April 2017
2	Professor Xia Dingguo, Peking University.	Breaking through the limitations of traditional modified methods such as doping, cladding and Nanoscale morphology, an O2-form lithium manganese-based power battery cathode material with specific capacity up to 400mAh/g was prepared by combining $LiMO_2$ phase with single-layer Li_2MnO_3 phase.	October 2018
3	Professor Zhao Tianshou, Hong Kong University of Science and Technology.	They proposed a cathode design concept to achieve good Li–S pouch cell performances. The cathode is composed of uniformly embedded ZnS nanoparticles and Co–N–C single-atom catalyst to form double-end binding sites inside a highly oriented macroporous host, which can effectively immobilize and catalytically convert polysulfide intermediates during cycling, thus eliminating the shuttle effect and lithium metal corrosion. The ordered macropores enhance ionic transport under high sulfur loading by forming sufficient triple-phase boundaries between catalyst, conductive support and electrolyte. This design prevents the formation of inactive sulfur (dead sulfur).	24 October 2020

Table 3: Research on power batteries by research institutes and universities in China. Edited by Ran Dong
Source: Ministry of Science and Technology of the People's Republic of China[28-29], Zhao, C., Xu, GL., Yu, Z. et al[30]

Electric Vehicle´s enterprises

From China's enterprise competition pattern, according to the cross-country insurance certificate data show that in 2019 the national new energy vehicle production of the top ten auto companies reached 690,000 vehicles. The top three vehicle manufacturing companies were BYD, BAIC and Geely, accounting for 15.3%, 9.7% and 6% of the Chinese market share.

From the technical research and development situation, the electric vehicles produced by various vehicles are mainly loaded with NMC batteries and LFP batteries, and the vehicle companies have also invested a lot of resources in the research of improving the energy density and safety performance of the batteries.

Due to the rapid and intensive R&D on battery technologies, some Chinese companies are taking a global leading position such as:

- BYD's on blade batteries
- GAC New Energy's on graphene batteries, and
- SVOLT New Energy's on cobalt-free batteries

Those three Chinese companies are taking a global leading market position due to their state-of-the-art technology development. They are currently entering the industry's leading positions.

Equipment manufacturers

The main Chinese domestic power battery manufacturers are: BYD, CATL, Tianjin Lishen, GOTION High-Tech, Optimum Nano, and Wanxiang.

The technology of LFP and NMC is relatively mature, and the large-scale production has been realized for some time.

However, the development of lithium battery is currently at a bottleneck stage. Major battery manufacturers and automobile enterprises are conducting research on the manufacturing process and battery positive materials, and the specific research situation is shown in **Table 4.**

No	Research enterprise	Research content and results	Time
1	CATL	The pioneering module less battery (CTP) technology, by simplifying the module structure, increases the utilization rate of the battery pack by 15% to 20%, reduces the number of components by 40%, increases the production efficiency by 50%, and increases the energy density of the battery pack by 10%-15%.	2019
2	BYD	Blade batteries, blade shapes for manufacturing process innovation, its battery pack volume utilization can be increased by 50%. CTP battery pack volume utilization can be increased by 15% to 20%, easier to achieve with volume energy density, lifetime is also increased accordingly.	March 29, 2020
3	GAC AION	Graphene battery, ultra-fast charging battery. 3DG (Three-dimensional graphene) graphene preparation technology, the initial formation of process packaging and engineering capabilities. The graphene-based super-fast rechargeable battery can reach 6 Coulomb (that is, it can be fully charged in 1/6 of an hour) and can be charged 80% in 8 minutes with a charging pile with high output power.	January, 2021
4	SVOLT	Cobalt-free battery, using monocrystal silicon cobalt-free material, is superior to NMC811 battery in terms of energy density and safety. NMCA quaternary positive material, the quaternary material also has the same energy density as the NMC811 battery while improving safety. In addition, security is improved, and costs are reduced.	July 9, 2019
5	HaiNa Battery	The world's first mass-produced sodium ion battery. The world's first low-speed electric vehicle with sodium ion batteries was demonstrated in 2018. The positive electrode is made of cheap metal oxide and the negative electrode is made of coal. Energy density up to 150Wh/kg. The cycle life is more than 4500 times, excellent high and low temperature performance, high safety, and fast charging.	September, 2020
6	CATL	CATL's first-generation sodium-ion battery. In terms of cathode materials, CATL has applied Prussian white material with a higher specific capacity and redesigned the bulk structure of the material by rearranging the electrons. In terms of anode materials, CATL has developed a hard carbon material that features a unique porous structure. High-energy density, fast-charging capability, excellent thermal stability, great low-temperature performance and high-integration efficiency, among others.	July, 2021

Table 4: Research on power batteries by Chinese battery enterprises. Edited by Ran Dong
Source: China Automotive Technology and Research Center Co. Ltd(CATARC)[1],
GAC AION[31], SVOLT[32], 科创版日报[33-34], CATL[35]

It can be noticed that:

- CATL supply chain layout is supporting a wide range of customers, application areas, the company has a strong technology and market positioning, developed NMC811 battery production, module less battery package group technology breakthrough, and vehicle joint venture plant, and has rapidly expanded the production capacity[1].

- BYD has based their batteries on lithium iron phosphate/lithium nickel manganese cobalt technology route, the later stage will gradually release production capacity, the introduction of lithium phosphate-based development of module less blade batteries, continue to expand production capacity, for power battery supply paving the way[1].

- HaiNa Battery's sodium-ion batteries are currently used for energy storage and as a replacement for lead-acid batteries. The cost savings in anode and cathode materials allow sodium-ion batteries to compete with lithium-ion batteries[34].

- CATL has also made another breakthrough in battery system integration and developed an AB battery system solution, which is to mix and match sodium-ion batteries and lithium-ion batteries in a certain proportion and integrate them into one battery system, and control the different battery systems through the BMS precision algorithm. The AB battery system solution can compensate for the current energy-density shortage of the sodium-ion battery, and also expand its advantages of high power and performance in low temperatures. CATL has started its industrial deployment of sodium-ion batteries, and plans to form a basic industrial chain by 2023[35].

Battery technology application status

The main technical route

The material of batteries is one key element of power batteries, and the technology is being under strong R&D focus.

The lithium-ion phosphate-based battery technology market share is expected to grow in the near future while the main technical development routes are:

- focusing on reducing cobalt from positive electrode to no cobalt,

- adding silicon to negative electrode and developing electrolyte to solid state[1].

The mainstream technology of negative electrode materials is artificial graphite, but the mainstream carbon negative electrode lithium storage capacity has basically reached the limit, in the long term, carbon silicon material is expected to become one of the development directions of anode materials[1].

Short and medium-term industrial battery systems

At present, the research focus is mainly on positive and negative electrode materials, electrolyte and membrane, as of 2020 the development of power batteries in China as shown in **Table 5**.

Short and medium-term industrial battery systems

No	Anode material	Cathode material	Main separator material	Electrolyte salts	Energy density of cell (Wh/kg)	Possibility of realization
1	Lithium iron phosphate	Graphite	PP	Lithium hexafluorophosphate, functional additive	110-210	Commercialized
2	Mainly lithium mang-anate, mixed with NMC2 or NCA3	Graphite	PP4 or PE1	Lithium hexafluorophosphate, functional additive	120-170	Commercialized
3	NMC333 or NMC523	Graphite	PE	Lithium hexafluorophosphate, functional additive	160-200	Large capacity battery to achieve small batch applications
4	NMC333 or NMC523	Lithium titanate or graphite mixed with soft carbon	PP & PVDF5	Lithium hexafluorophosphate, functional additive	80-140	Commercialized
5	NMC622 or NMC811 or NCA	Graphite	PE, Thin and coating modification	Lithium hexafluorophosphate, functional additivet	220-250	The small capacity den-sity realizes the scale application
6	NMC622 or NMC811 or NCA	Graphite/ Silicon carbide	PE, Thin and coating modification	Lithium hexafluorophosphate, functional additive	250-300	Commercialized
7	5V(volts) Manganese acid lithium	Graphite	PE, Thin and coating modification	Lithium hexafluorophosphate, functional additive	200-240	Under development
8	Lithium-rich layered lithium manganate	Graphite	PE, Thin and coating modification	Lithium hexafluorophosphate, functional additive	220-280	Under development
9	Lithium-rich layered lithium manganate	Silicon carbide	PE, Thin and coating modification	Lithium hexafluorophosphate, functional additive	280-400	Under development

Table 5: Short and medium-term industrial battery systems (up to 2020)
Source: China International Battery Fair 2018[36]

[1]**PE:** Polyethylene
[2]**NMC:** Lithium nickel manganese cobalt oxide battery
[3]**NCA:** Lithium nickel cobalt aluminum battery
[4]**PP:** Polypropylene
[5]**PVDF**: Poly (vinylidene fluoride)

LFP battery was used in the initial development of new energy vehicles. This technology route, with low energy density but good safety, has become the first choice of power batteries for the ”early generation” of new energy vehicles. However, with the intensification of competition in the new energy vehicle market, NMC batteries with higher energy density and better cost efficiency ratio have become the new favorite and are still the mainstream of the market until now.

The CTP technology of CATL improves the energy density and group efficiency of NMC battery, and the blade battery developed by BYD improves the energy density and safety performance after group based on the low cost of LFP battery.

LFP battery market share expected to grow.
However, professionals in the industry point out that the energy density of LFP and NMC battery is close to the theoretical limit, the energy density limit of high nickel material + silicon carbon negative cell is about 300 Wh/Kg At current time only CATL and GOTION High-Tech have reached this level[37].

PART FOUR
TRL ESTIMATION OF CHINESE BATTERY TECHNOLOGY

Technology Readiness level (TRL) is originating in the 1960s from the NASAs approach to send man to the moon. The main purpose of TRL estimations is to estimate the maturity of technology in relation to when technology is being ready for real life implementation and commercial usability of technologies.

It should be noticed that there are other aspects of readiness such as social, societal and political. In our research reported in this paper we focus on the technology readiness only of those main battery technologies we see has evolved in the Chinese context.

Estimation of battery's TRL in China

TRL (Technology Readiness Levels) of batteries in China is shown in Figure 4.

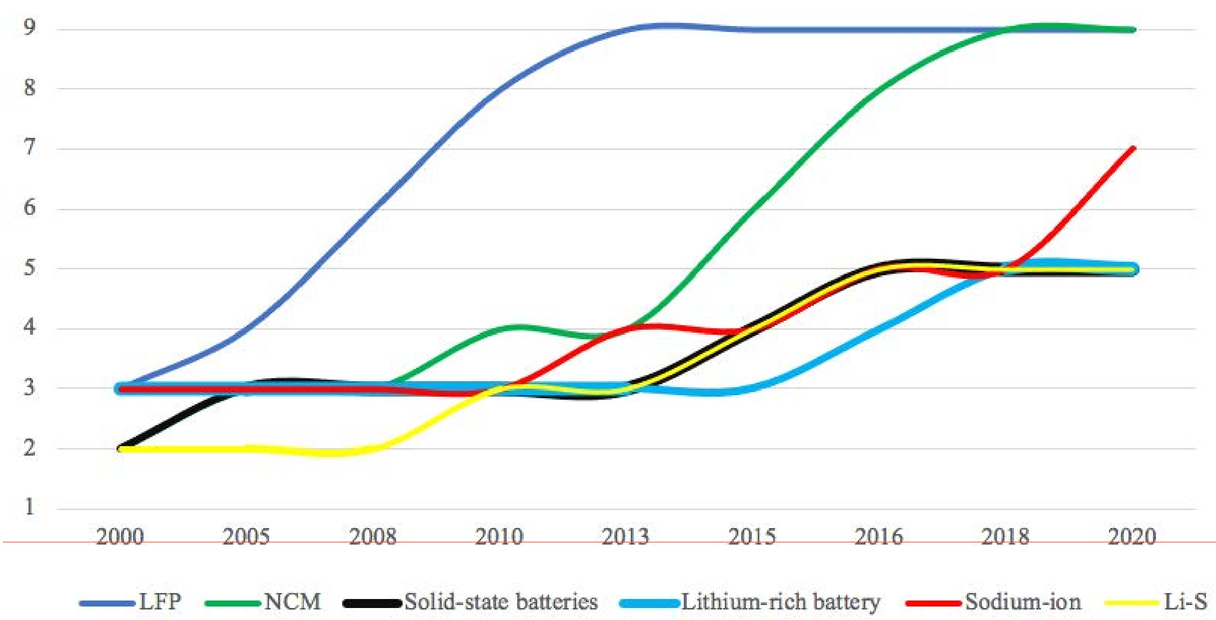

Figure 4: Estimated battery's TRL in China
Source: Edited and drawn by Ran Dong

The following is the analysis and prediction of TRL development trend represented in the TRL estimations shown in **Figure 4**.

- It can be seen from the figure that TRL of LFP battery reached level 9 earlier in China, corresponding to the rise of China's new energy vehicle market in 2013.

- NMC battery followed, reaching Grade 8 and entering the market around 2016.

- Sodium ion battery, as a new type of battery that is easy to use, has been successfully developed by Chinese battery manufacturers and loaded with vehicle experiments. It is now being prepared for commercial use and is at level 7.

- As the cost of sodium is much lower than that of lithium, it is expected that TRL of sodium ion battery will rise to level 8 or even directly to level 9 in a very short time.

- Solid-state lithium-ion battery, as the most promising new technology of battery and as the estimated mainstream power battery in the future, has always been a research difficulty in the development of solid electrolyte. At present, only the samples of battery cells are available, and the charging and discharging times of battery cells are far from meeting the requirements of power battery, ranking at level 5.

The all-solid-state battery is expected to be ready for commercial use by 2030, reaching grade 9. The research difficulty of lithium-rich cathode battery lies in the research of cathode materials, which is still at grade 5. If lithium-rich cathode materials cannot break through the technological difficulties, the TRL in the next few years will still be at grade 5.

New batteries technologies

The following is a compilation of some of the new battery research mentioned in **Figure 4** that could be used as power batteries for electric vehicles.

Li-S battery

The design of Li-S (Lithium-Sulfur) batteries was first proposed in the 1960s, but progress has been slow. It was not until the 21st century that China's research on Li-S batteries began to develop gradually.

From 2009 to 2013, some progress has been made in the research of electrolyte and cathode materials of Li-S batteries.

By 2015, the existing research results involved the preparation process of cathode materials, and the electric performance experiment of batteries also had some research results.

In 2016, Chen Jian from Dalian Institute of Chemical Physics, Chinese Academy of Sciences and his team developed nanostructured carbon-sulfur composites, high-sulfur load-carrying positive anode plates and large-capacity Li-S batteries.

The rated 37Ah Li-S battery developed by the team has a mass specific energy of 566 Wh/kg at room temperature and 616Wh/kg at 50°C, and has passed the third-party safety test, which is also the highest rated capacity and energy density Li-S battery reported so far.

At the same time, the research team has also made new progress in the group technology of Li-S batteries. The 1 kWh Li-S battery pack developed by the third party has a specific energy of 330 Wh/kg[38]. The technology readiness is in level 5.

Figure 5: Li-S battery cell and solid-state lithium-ion battery cell produced by Chinese Academy of Sciences

Source: DaLian Institute of Chemical Physics, Chinese Academy of Sciences[38], NingBo Institute Materials Technology & Engineering, Chinese Academy of Sciences[38]

Solid-state lithium battery

Although the research of solid-state lithium battery started earlier, the research of materials, especially the research of non-hydrolyzed electrolyte, has made slow progress so far[39].

- According to the 2016 "Chinese Academy of Sciences, research progress of high energy density lithium battery letters" the Qingdao institute of bioenergy and the Chinese Academy of Sciences Cui Guanglei researcher and his team for polyethylene oxide (PEO) low ionic conductivity at room temperature, working on to solve the potential window narrow bottleneck problem. They started from the molecular structure to improve the ionic conductivity, combined with multi-scale mechanisms of ion transport mechanism and kinetics of transmission. They designed a new type of solid polymer electrolyte, the electrolyte conductivity at room temperature that can reach 4.3×104 S/cm, and has a wide electrochemical window.

- Xu Xiaoxiong and his team from Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences developed 1-8Ah series solid state battery cells with composite inorganic materials as solid electrolyte and lithium metal oxide as positive and negative electrodes[39], respectively. The technology readiness is estimated to be on the TRL level 5.

- As early as 2016, CATL - a leading power battery company, officially announced its research and development path in the sulphide solid state battery. Currently, CATL's solid state battery can achieve a 300-week cycle with a capacity retention rate of 82%, but the all-solid-state battery is still under development and is expected to be commercialized after 2030.

- Prologium will launch MAB solid-state batteries package adopted Bipolar + (internal series-parallel batteries, etc.), S - Inlay (linear stack) with Logi - Pack (built-in detection system) technology, in view of the high security, high heat capacity solid-state batteries and institutional characteristics and develop a whole new way to encapsulate and plans in 2022 to achieve safety and economic feasibility of the scheme to create range with high energy density fuel car battery pack[37].

- e. In addition, Ganfeng Lithium Phase 1 project solid-liquid mixed semi-solid lithium battery to achieve large-scale production capacity, the company and the Chinese Academy of Sciences Xu Xiaoxiong research group, set up a wholly-owned subsidiary Zhejiang Feng Li New Energy Technology Co., Ltd., to carry out solid-state lithium battery industrialization work[37].

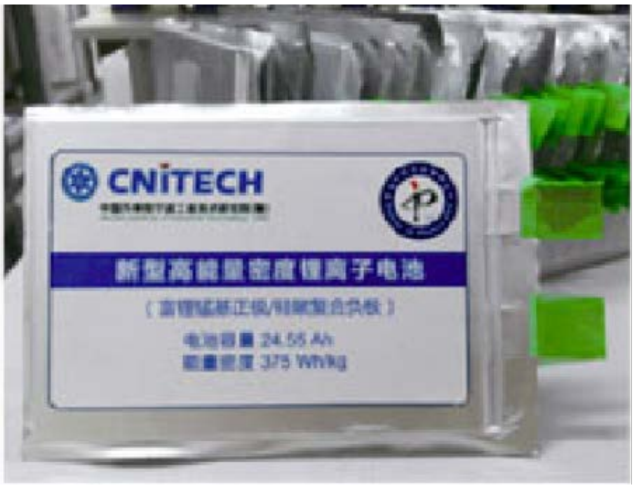

Figure 6: High energy density Li-ion batteries using Li-rich layered cathode

Source: NingBo Institute Materials Technology & Engineering, Chinese Academy of Sciences[40]

In 2016, by using lithium-rich manganese-based samples from the pilot scale experiment, power lithium-ion battery research team combined Li Hong researcher, institute of physics, Chinese Academy of Sciences and his team, using high-capacity nanometer silicon carbon anode materials. This cross-institute cooperation has developed a soft package of lithium-ion battery cell with a capacity of 24 Ah, the quality of the energy density of 374 Wh/kg, the volume energy density of 577 Wh/L.

Its energy density is about twice that of lithium-ion batteries (its energy density is about 180Wh/kg) based on lithium manganese phosphate/ternary composites (NMC) that we developed earlier[40]. The technology readiness is on the TRL level 5 at present time.

Sodium-ion battery

Sodium-ion battery is a research hotspot in China.

On December 8, 2020, a new R&D program called ”New Energy Running out of” Acceleration ”was broadcast by the” Half Hour Economy ”of CCTV2 financial channel, in which the Sodium-ion battery developed by a research team of the Institute of Physics of the Chinese Academy of Sciences was reported. The comprehensive performance of the Sodium-ion battery was developed by the HaiNa Battery’s Sodium-ion research and development team. The energy density is reported to be close to 150 Wh/kg, the cycle life has reached more than 4,500 times, the high and low temperature performance is reported to be excellent, the safety is estimated to be high, it has the fast-charging ability, and it is one of the leaders in the field internationaly, and has begun the process of commercialization.

Contemporary Amperex Technology Co., Ltd. (CATL) successfully held its first online launch event “Tech Zone” on July 29, 2021. Dr. Robin Zeng, chairman of CATL, unveiled the company’s first-generation sodium-ion battery, together with its AB battery pack solution - which is able to integrate sodium-ion cells and lithium-ion cells into one pack - at the event.

CATL has been dedicated to the research and development of sodium-ion battery electrode materials for many years. In terms of cathode materials, CATL has applied Prussian white material with a higher specific capacity and redesigned the bulk structure of the material by rearranging the electrons, which solved the worldwide problem of rapid capacity fading upon material cycling. In terms of anode materials, CATL has developed a hard carbon material that features a unique porous structure, which enables the abundant storage and fast movement of sodium ions, and also an outstanding cycle performance[35].

Figure 7: Performance comparison of CATL’s first generation sodium ion battery and LFP battery

Source: Sodium-ion battery launch event, CATL[35]

Figure 7 shows the performance comparison of CATL’s first generation sodium ion battery and LFP battery. Based on a series of innovations in the chemistry system, CATL’s first generation of sodium-ion batteries has the advantages of high-energy density, fast-charging capability, excellent thermal stability, great low-temperature performance and high-integration efficiency, among others. The energy density of CATL’s sodium-ion battery cell can achieve up to 160Wh/kg, and the battery can charge in 15 minutes to 80% SOC at room temperature. Moreover, in a low-temperature environment of -20°C, the sodium-ion battery has a capacity retention rate of more than 90%, and its system integration efficiency can reach more than 80%. As of now, CATL has started its industrial deployment of sodium-ion batteries, and plans to form a basic industrial chain by 2023[35]. This technology is estimated to be on the TRL level 7 at present time.

Forecasted the development of power batteries

Research on new materials for lithium batteries

The development of lithium battery is in the bottle-neck stage of the technology capacity and the energy density is close to the physical limits of that technology.

The battery material in **Figure 8** is favored by the battery industry and may be a breakthrough in breaking the limits of contemporary Li-ion battery barriers.

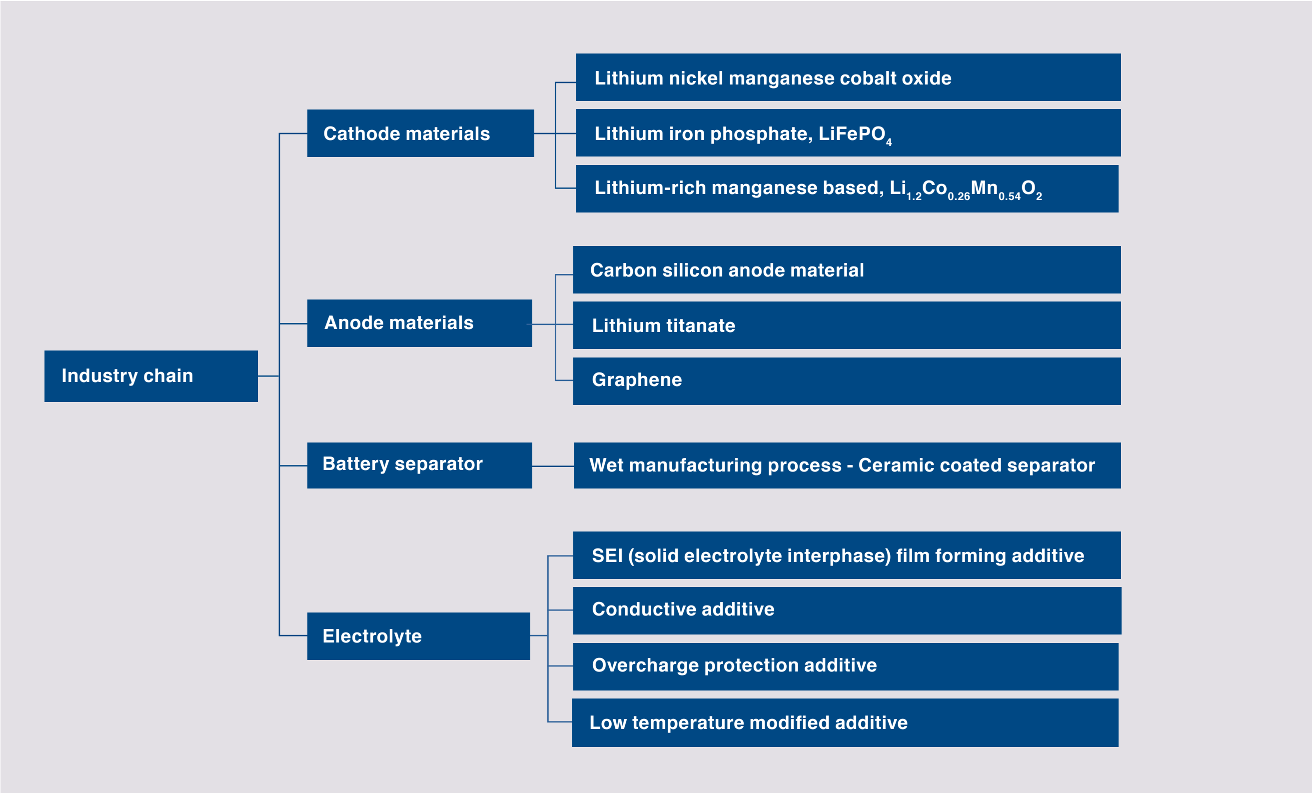

Figure 8: Some of the new materials concerned by the industry

Source: 2020 the development of power batteries in China [1], China International Battery Fair 2018[36]

Figure 8 indicate some key technology routes that are taken to develop battery technologies and to manage the bottleneck of existing lithium material technology in China.

Based on the **Figure 8** we can see some main development directions:

- **Cathode material:** Under the influence of new energy vehicle subsidies tend to subsidize high mileage and high energy density models, NMC battery with high nickel content is the mainstream of development at present[1].

- **Anode material:** Artificial graphite is the mainstream technology. The lithium storage capacity of mainstream carbon cathode has almost reached its limit, and the space for rise is limited. Carbon silicon material is one of the future development directions. The specific capacity of carbon silicon material is high, but the cyclic ratio performance is poor, which needs to be improved[1].

- **Battery Separator:** Battery separator has the highest technical barrier among the four major materials of power battery. With the rapid growth of lithium-ion battery with Nickel manganese cobalt(NMC) cathode material, wet separator replacing dry separator is the main development trend in the future. The technical route is as follows:

  1. Wet battery diaphragm technology complies with the high energy density requirement of power battery.

  2. Wet stretching is mainly aimed at low density polyethylene (PE) material, which is mostly used in NMC battery.

  3. Dry tensile mainly for polypropylene (PP) materials, mostly used in lithium iron phosphate (LFP) batteries[1].

- **Electrolyte:** Electrolyte is the most mature technology among the four materials of power battery, and there is little risk of technical complications. The product homogeneity is serious, and the formulation of additives becomes the key to the improvement of electrolyte performance[1].

Separation of batteries and electric vehicles is becoming a trend in China

Driven by policies and markets, the domestic electricity conversion model will continue to heat up in 2020. The new subsidy policy strongly supports the separation of vehicle and battery mode. Then, as an important part of the new vehicle-battery infrastructure, the power batteries swapping station was first written into the government's work report in 2020 and were listed on the national strategy list. This developing mode is promoting the general development of platform-based battery packs, to achieve the compatibility of different vehicle models and different battery technology routes, to achieve a standardization and achieve a reduction of the cost via scale of economy. There are still some challenges in the battery-swapping domain, such as lagging laws and regulations on the separation of vehicles, inconsistent battery standards, high construction costs of swapping stations, business model under development etc.

Solid-state batteries hold broad prospects

The limit of the energy density of lithium-rich Mn-based + silicon carbon cathode is around 400 Wh/Kg. China has set a goal with another five years to increase the energy density by 33% by 2025. But the closer the R&D process gets to the theoretical limits of this route, the lower the marginal output of R&D inputs and the slower the pace of progress.

In this context, solid-state lithium-ion batteries are the most likely next-generation lithium battery technology. The energy density of solid-state batteries has the potential to exceed 500 Wh/kg, and more energy density means longer vehicle driving range. Solid-state lithium-ion batteries, which replace traditional organic liquid electrolytes with solid-state electrolytes, are expected to fundamentally solve battery safety problems, and are ideal chemical power sources for electric vehicles and large-scale energy storage[37].

According to the calculation of SNE Research, the global demand for solid-state batteries is expected to be close to 500 GWh in 2030, and the global market space for solid-state batteries is expected to reach 6 billion yuan in 2025, while the market space for solid-state batteries in China is expected to reach 3 billion yuan in 2025 and 20 billion yuan in 2030.

Overall, from a long-term perspective, solid-state batteries have broad prospects and are likely to become the mainstream batteries in the future. However, from the current situation, the technical level and cost problems restrict its large-scale commercial use, and liquid batteries are still the necessary option[37].

Key factors include the preparation of solid electrolytes with high room temperature conductivity and electrochemical stability, high-energy electrode materials suitable for all solid-state lithium-ion batteries, and improved electrode/solid electrolyte interface compatibility.

Recycling of decommissioned batteries has good market prospects

In the New Energy Vehicle Industry Development Plan (2021-2035), an efficient power pool recovery system is proposed. Based on the sustainable development of new energy vehicles, the production responsibility extension system is implemented, the construction of the traceability management platform of power batteries of new energy vehicles is strengthened, and the whole life cycle of power batteries can be traced[27].

According to the development of the existing market, the market size of power lithium battery pack recycling will reach about 6,5 billion yuan by 2020, of which the market size of ladder utilization is about 4,1 billion yuan, and the market size of recycling is 2,4 billion yuan.

By 2023, the total market size will reach 15 billion yuan, of which the market size of ladder utilization is about 5,7 billion yuan, and the market size of recycling is about 9,3 billion yuan.

The market for power battery recycling is expanding and will be the next profit-taking point.

Challenges

Power battery safety issue

In China, data from the Defective Product Management Center of the State Administration for Market Regulation shows that as of the first half of this year, China has recalled electric cars whose power batteries were found to be unsafe. The recall times of electric vehicles are 141 batches. A total of 840,500 electric vehicles have been recalled, most of which are related to the fire problem of new energy vehicles.

In a series of new energy vehicle recall accidents, there are many reasons directly pointing to the power battery, which in addition to the negative impact on the brand image of the car companies, will also make the supporting power battery companies in the brand image, economic losses and strategic objectives are hit.

The main breakthrough points to improve safety performance are new diaphragm, new electrolyte, electrode safety coating, battery design optimization, new materials, etc. Breakthroughs in these key issues will not only greatly improve the safety performance, but also play a role in the improvement of battery energy density.

BMS (Battery Management System) upgrade

With the increasing energy density of batteries, the requirements on the operating environment of the batteries becomes higher and higher. So, every part of the battery operation is becoming more and more sophisticated. If there is a problem in one place, it may affect other parts. So, a car's battery safety performance is not actually the battery itself long ago. Even battery performance depends on more than just the battery itself.

To improve this situation, OEMs (original equipment manufacturers), battery manufacturers, and software companies that access driver data need to work together. Based on 5G technology, big data management, and "Internet of Things", a battery management system with full functions, high efficiency and fast communication has been designed and implemented.

Recycle decommissioned batteries

According to the China Automotive Technology and Research Center, more than 200,000 tons of power batteries will be phased out in China by 2020, with a market value of 17,5 billion yuan. There is a wave of battery retirement coming. Although the power battery recycling market is generally optimistic in the industry, China's power battery recycling technology and systems are under development.

From the perspective of resource utilization, it is troublesome waste of resources to directly recycle decommissioned power batteries as raw materials before they are fully utilized.

In the Interim Measures for the Administration of Recycling and Utilization of New Energy Vehicle Power Batteries jointly issued by several ministries and commissions of the state, it is proposed that the utilization of retired power batteries should follow the principle of first step utilization as the second and third life of batteries before entering the recycling stage. That is, decommissioned power battery after the ladder utilization, and then recycling.

PART SIX - CONCLUSIONS

From the perspective of regional distribution, the global total production of new energy vehicles in 2019 is 2,21 million, China accounts for more than 50%[41-42]. China is the world's largest market for new energy vehicles in general and electric vehicles in particular.

From the perspective of installed capacity, power battery, as the core component of new energy vehicles, plays a key role in promoting the development of new energy vehicles. Driven by the new energy vehicle industry, the power battery industry has maintained rapid growth.

The installed capacity of new energy vehicle power batteries reached 56,89 GWh in 2018 and 62,89 GWh in 2019, an increase of 0,5% compared with 2018.

Affected by the epidemic situation in 2020, the expected sales target of China's new energy vehicles is the same as that of 2019, and the installed amount of power batteries is also close to that of 2019[43-44]. It is expected that in the short to medium term, power battery is still the main power source of new energy vehicles.

From the perspective of technology research and development, in 2020, there will be several innovative changes in the field of domestic power battery technology, mainly focusing on the two goals of reducing battery cost and improving product performance. Specifically, the current power battery innovation technologies include: no battery pole ear, blade battery, CTP (Cell to Pack), JTM (Jellyroll to Module) and other battery pack integration schemes; Cobalt-free, quaternary battery material system upgrade; "No fire", "Million kilometer" battery, etc.

From the perspective of technology maturity, LFP battery and NMC battery have been put into the market on a large scale and become the main technology route of major Chinese battery manufacturers at present, ranking at the TRL level 9. However, the energy density of the two main types of batteries has reached the upper limit, so it is necessary to focus on the research of batteries with new materials. As for the research of new batteries, Li-Mn-based batteries and solid-state batteries have very high cell energy density and good safety performance, which are the focus of domestic research at present. At present, the two types of batteries have only completed the charging and discharging experiments of the battery cell under the laboratory conditions, and it will take some time before the mass production and commercial use can take place. They are estimated to have reached TRL level 5.

China imports 70 per cent of its lithium, so, sodium-ion batteries, which are relatively easy to use, are also a research hotspot. HaiNa Battery is the first sodium ion battery manufacturing company with independent intellectual property rights in China. The sodium ion batteries researched by the company have been loaded in low-speed vehicles and are now ready for mass production.

On July 29, 2021, CATL announced its first generation of sodium ion batteries. The energy density of CATL's sodium-ion battery cell can achieve up to 160Wh/kg, and the battery can charge in 15 minutes to 80% SOC at room temperature. As of now, CATL has started its industrial deployment of sodium-ion batteries and plans to form a basic industrial chain by 2023[35]. They are estimated to have reached TRL level 7.

From the market perspective, China's previous power battery route was mainly NMC battery and LFP battery as alternate use. LFP batteries, with their advantages in cost and safety, will become active again in the field of new energy passenger vehicles in 2020 under the dual effect of further declining subsidies and breakthroughs in battery technology. However, if both cobalt-free batteries and graphene batteries can be mass-produced and marketed in the future, they will have a great impact on the power battery market and new energy vehicle market based on their advantages of reducing costs and improving safety performance.

In short, in the context of increasingly improved domestic standards and gradually adjusted policies, combined with the integration of 5G, big data and other new technologies, the future power battery will form a complete industrial chain from production to recycling, and achieve a complete tracking and traceability in the battery life cycle, to promote the rapid development of new energy vehicles, electrical vehicles can achieve comprehensive popularity in the future. By then, fuel vehicles will withdraw from the historical stage, to achieve the purpose of energy saving, emission reduction, low carbon, and environmental protection.

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