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Manufacturing Competency: Roots of Competitive Advantage of Chinese Electric Vehicle Battery Industry

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Abstract: China's leading development of a complete battery value chain for Electric Vehicles (EV) is restructuring the global automotive sector. The competitive advantage of China's EV battery industry lies on its firms' core competency and political economic geography. Based on first-hand empirical material and data obtained from years of fieldwork in an EV battery cluster in South China, this paper identifies what the Chinese EV battery industry's core competency is and details how it is built up from below. The current core competency of Chinese battery firms is their mass manufacturing capability to supply lithium-ion batteries vehicle manufacturers (OEMs) with stable and consistent quality as well as competitive prices. This competency is acquired by firms through technological learning at workshop level while taking use of their experiences accumulated in mass production of batteries for consumer electronics sectors. Furthermore, the rapid learning and accumulation of knowledge on battery manufacturing at large scale is also facilitated by the industrial cluster environment where firms are embedded. Supported and promoted by local government policies, Chinese EV battery clusters are composed of firms from different segments of a complete battery value chain. The findings illuminate the likely strategic strengths, weaknesses, and futures of the Chinese EV battery industry in global competition.

Keywords: Electric Vehicle (EV); Lithium-ion Battery; Core Competency; Industrial Cluster; Supply Chain; Manufacturing; China

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1. Introduction

The automobile industry is now experiencing historic disruptions of digitalization of products and services, electrification of powertrain, and transformation of the whole value chain structure [1] (pp.121-136). Electrification has reduced the number of components from 1400 for internal combustion engine powertrain to 200 for battery electric vehicle powertrain, making batteries and related components become key parts of electric vehicles (EV) and battery firms play key roles in reshaping the automobile industry. Electric powertrain occupies 30-45% of whole car cost and power battery occupies 75-80% of the powertrain cost, thus having the highest value added in an electric vehicle [2]. EV battery making is so important in automobile electrification that it is even predicted that those who conquer battery will control the electric vehicle market [3] (pp.156-177).

In EV battery sector, China is now the global lead market, the major producer, and a key innovator [4]. In 2020, installed EV batteries in China reached about 63 Gwh, 46.8% of the world installation (63/134.5 Gwh). In 2021, China represents 74% (465/631 Gwh) of global EV battery production capacity which increased 84% than in 2019 [5]. China will continue to be the largest EV battery producer in the next 10 years. Though the rapid expansion of the NEV battery sector along with massive speculative investment globally and in China is propelling overcapacity in battery production, with the demand for batteries ramping up with 30% year-over-year growth around the world and reaching 3 900 Gwh in 2030, additional capacities are still needed from 2023 onward [6].

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Relying on increased scale economies and technology advancements, Chinese firms have become cost leaders in global competition. In 2019, the average battery pack price in China reached $147/kWh, the lowest in the world. In 2021, China brought the global average battery pack price down to $132/kWh, even with the rising prices of materials and cell components.

China's competitive advantage in EV battery is more qualitative than shown by quantitative indicators [4]. China caught the opportunity of the disruptive transformation of automobile industry towards digitalization and electrification and gained a leading position by acting as the first mover in EV battery making. This first mover advantage is illustrated by Chinese battery firms' accumulated experience in mass manufacturing of EV batteries and steep learning curve effect. China is the first in creating a complete EV battery value chain, from upstream materials production to midstream manufacturing of cells, modules, BMS (battery management system), and packaging, as well as downstream applications in mobility and various other fields, such as grid storage, lighting, solar energy, and movable storage, thus, forming a vertically specialized new sector of energy storage. Within the automotive sector, Chinese battery producers are becoming important players as providers of core components, reaching out into other battery technologies such as fuel cells. Furthermore, China controls tightly the "upstream" activities such as mining and refining of rare metal material with large state-owned firms, and develops quickly the "downstream" activities such as battery recharging and recycling sectors, reinforcing its leading role in global supply chains. Global automobile supply chain development, therefore, is no longer a top-down process, controlled by the leading global brand-name OEMs (original equipment manufacturers) in industrialized countries, but multidimensional in the sense of distributed centers of innovation and industrial players controlling different segments. Being the first in creating a complete EV battery supply chain and a distinctive energy storage sector in the world thanks to the emergence of EV market, China has gained a whole-value-chain advantage in global competition.

This competitive advantage of China's battery sector is due to all kinds of reasons, including the national industrial policy, Chinese market size, the legislation regarding EV in place, the existence of vast natural resources [3] (pp.156-177), and especially firms' specific strategy of "specialized vertical integration" [7] (pp.178-201). Major firms expand and integrate their activities into different stages of the production system, but vertical integration remains within the battery value chain and around the specialized field of battery or electricity storage. This vertical integration enables related Chinese firms to grow fast and maintain leading positions in production technology based on long-term strategic investment [3] (pp.156-177). However, due to difficulty of access to empirical field, little detail is known about the underlying base of verticalization strategy of Chinese battery firms as well as the origins of competitive advantage of Chinese battery sector [8]. According to strategic management theories, core competency is the very logic foundation of competitiveness of firms [9] (pp.79-91),10(pp.38-49).

Based on the competency perspective and primary firm-level evidence collected from a case study of Chinese EV battery cluster, this paper tries to reveal the deep roots of verticalization strategy and competitive advantage of Chinese battery firms, by qualifying their core competency and describing how it has been built up from the bottom of value chain. We argue that the nature of core competency of Chinese EV battery firms is by far their mass manufacturing capacity of LFP (lithium-iron phosphate)-dominated EV battery cells, modules, and packs including BMS with good quality/price ratio, accompanied by the capability of rapid production capacity scaling up through aggressive fixed assets investment. Although local government support is important, this core competency is essentially built up from the bottom by Chinese firms within regional battery clusters. We identify two key processes that determine jointly the formation of core competency:

One process, external to firms, is clustering of EV battery manufacturing activities at regional level with strong local government policy support across China. Detailed analysis of the EV battery industry in Huizhou shows that industrial cluster at regional level is characterized by quite complete value chain within it, even with a small number of small and medium sized firms who establish user-supplier linkages. Therefore, industrial cluster constitutes a "thick" ecosystem for manufacturing firms which can find easily accessible specialized resources and capabilities, such as skills, funding, precompetitive R&D, suppliers, facilities, and industry knowledge in proximity [11]. Specialized EV battery cluster creates a favorable microenvironment where local firms can draw on these capabilities and combine them with their own internal resources to learn manufacturing technologies through interaction with other upstream or downstream firms in the same value chain.

The other process, internal to firms, is the shop-floor level technological learning of mass production of EV battery. The learning curve effect in EV battery is 18% cost reduction for every doubling of battery production capacity [5]. Through mass production and rapid investment in most advanced equipment, Chinese local battery firms adopt very down-to-earth approaches of learning by doing, by using, and by interacting among suppliers, all appropriate to the intrinsic requirement of mastering collectively matured lithium-ion EV battery technologies. Therefore, China's EV battery manufacturing has formed up from production and assembly lines a complex system combined of advanced equipment, cell designs, production engineering plans, production procedures and organizations, and workers' skills and know-hows. Chinese battery makers have accumulated significant experience, which links the rate of price declines to the cumulative volume of battery packs deployed on the market. With these production capabilities in place, they also have a potential to accelerate the rate of cell design improvement and reducing costs.

The remainder of the paper is organized as follows. Following this introduction, Section 2 gives a geographic overview of industrial clustering of EV battery manufacturing in China, taking into account of national and local policies on battery sector. It introduces Huizhou battery cluster as a specific case and explains research methodology. Section 3 identifies the nature of core competency of local battery manufacturing firms in using firm examples in Huizhou cluster to illuminate the internal process of practical learning of battery production technology. Section 4 discusses some broader implications of core competency of Chinese battery firms, including the way that core competency constitutes the strategic base of specialization and verticalization of Chinese battery firms along the value chain and implications to EV industry structure, government policies, as well as automobile OEMs. Section 5 concludes our findings and arguments.

2. Chinese EV Battery Clusters as Local Manufacturing Ecosystems

Although the car industry as a whole is not a strategic sector under "Made in China 2025", electric vehicle (called New Energy Vehicles or NEV in Chinese policy terms) is selected as one of the ten strategic emerging industries of this program and received massive support from the state. Chinese government hopes that NEVs will help the country transform from a follower to technological leader in the automobile sector, reduce China's dependence on imported oil, and improve the country's overall environment quality. Besides promoting massive EV market demand, the state employed effort to generate enough supply of EVs, batteries, and other key components, in which the EV batteries was regarded as an important industry in the 2020s and beyond. From 2016 to 2018, central government published the famous "whitelist" of battery producers which were all Chinese firms, an industrial policy to subsidize only the EVs powered by batteries made by domestic producers. In general, the EV policy of China targeted the supply of raw materials by Chinese mining companies, the production of batteries by Chinese battery makers, and the local production of EVs using Chinese batteries [3] (pp.156-177). In 2017, China's central government published its first national plan for the battery industry, setting the goal of becoming an "technologically independent storage superpower". It also contains policies that would increase domestic demand for grid-scale storage as part of the energy sector development [12].

2.1. Emerging EV Battery Clusters: From National to Local Policies

The national strategy of developing battery sector as a strategic emerging industry was quickly diffused and assimilated into local governments' implementation at provincial, city, township, and district levels. Chinese local governments have stronger incentives to support production than consumption, and have habit and ambition to cultivate large scale, leap-frogging local champions, to become suppliers to brand-name car OEM producers [13]. Almost all the provinces have targeted EV industry as development focus. And since it is difficult to obtain OEM projects, most of them turned to push battery production and supply in selected regions or areas. The local implementation of national EV industry development strategy has resulted in massive regional emergence of EV battery manufacturing clusters geographically across the whole country, as well as domestic redundancy and fierce competition. According to Bloomberg New Energy Finance, in 2017, China had 235 firms producing batteries, and 8 out of 13 major battery manufacturing sites world-wide were in China. In 2018, the "Catalog of Recommended Models for the Promotion and Application of New Energy Vehicles" issued by the Ministry of Industry and Information Technology (from the 5th batch in 2018 to the 11th batch in 2018) listed out more than 190 power battery firms. Their geographical distribution is concentrated in eastern and southern coastal regions, including 112 in East China (59%), 29 in South China (13.7%), 23 in Central China (12%), 13 in North China (6.8%), 9 in Southwest China, 5 in Northwest and 5 in Northeast regions. Raw materials mining and extracting are concentrated in western regions, which cell materials and components are located more widely than mining, and many are near locations of cell and pack production (Table 1).

Table 1. Geographic distribution of EV battery manufacturing in China.

Regions/Provinces	**Number of EV Battery Producers**	**Exemplary EV Battery Producers**	**Raw Material & Cell Components Producers**
Eastern China:	**112**		
Shandong	10	Yuhuang New Energy, Guojin Battery, Mofang New Energy, Wina Battery, Zibo Guoli, Gotion High-Tech, Lishen Battery	
Jiangsu	41	CATL, Phylion, Chunian, Youlion Battery, TENPOWER, Horizon New Energy, Jiaweilong Solid-state Energy Storage, Gotion High-Tech, Lishen Battery, Farasis, LG, SK, etc.	
Zhejiang	22	Microvast, Tianneng Power, Chaowei, CRRC New Energy, WM Motor, Aoyou Battery, Weihong Power, Wanxiang 1-2-3, Gushen Energy, and Hengdian Dongci	Huayou, Shanshan Technology
Shanghai	15	CATL, DLG Battery, ATBS, Hope New Energy, Shanghai Wolkswagen, SAIC Motor, Delang Energy Power, Jiexin Power, Carnegie New Energy, and Jinghong New Energy	
Anhui	12	Gotion High-Tech, ETC Battery, SinoEV, Wuhu Tianyi Energy, Farasis	Huayou
Jiangxi	7	CATL, Farasis, Far East Battery, Anchi New Energy, Hengdong New Energy, Gotion High-Tech	Huayou, Tinci High-tech Materials
Fujian	5	CATL, EPOWER, Jiudian, Mengshi, and Guancheng Ruimin New Energy	
Central China:	**23**		
Hunan	8	Soundon New Energy, Melsen Power, BYD	Corun New Energy
Hubei	6	Wuhan Troowin Power, LiWei Renewables, Camel Group New Energy, and Dongfeng Motor, Lishen Battery, EVE Lithium Energy	

Henan	9	CALB (Luoyang), DFD Group, Poly Fluoride (Jiaozuo), Henan Lithium Power Source, Henan New Taihang, BAK	
Northern China:	**13**		
Beijing	7	National Power Battery, CITIC-Guoan Mengguli, SinoHytec, Haibo Sichuang Technology, Zhixing Hongxn, Zhixing Hongyuan, and Beijing Pride	
Tianjin	5	Yingalde, Lishen Battery, Jeve, Hawtai-EVE, and Gateway Power	Huayou, Tinci High-tech Materials
Shanxi	1	Changzheng	
Hebei	1	Gotion High-Tech	
Inner Mongolia			Huayou, Shanshan Technology
Southwestern China:	**9**		
Sichuan	5	CATL, Jianxing Lithium Battery, Tonghua Technology, Dongfang, Guorong Technology, Lishen Battery, BAK	
Guizhou	1	Gui'an Sunshine Renewables	
Chongqing	2	Chang'an, BYD	
Northwestern China:	**5**		
Shaanxi	4	Tesson, Xinghua Electronics, Banghua, Samsung Huanxin	
Ningxia	1	Longneng Technology	
Qinghai			CATL, BYD, China Minmetals
Gansu			Jinchuan
Northeastern China:	**5**		
Liaoning	2	BMW-Brilliance, Panasonic	
Heilongjiang	1	Harbin Guangyu Battery	Battery NM
Jilin	2	FAW-Volkswagen, BYD	
Southern China	**29**		
Guangxi	3	Zhuoneng Renewables, Sunwatt Battery, Gotion High-Tech	
Guangdong	26	CATL, BYD, Yinlong New Energy, Tianjin New Energy, EVE Lithium Energy, BAK Battery, Penghui Energy, Zhenhua New Energy, Sunwoda, EPower Energy, Cham Battery, Maike New Energy, GAC Group, Teamgiant, TIG, BAK, SK	Corun New Energy, Gotion High-Tech, Shanshan Technology, Battery NM

Note: Battery producers in table refer to firms whose main business is making battery semi-finished and finished products, i.e., cells, modules, and packs with battery management system.Sources： i) Data about Battery Producers is based on the "Catalog of Recommended Models for the Promotion and Application of New Energy Vehicles" issued by the Ministry of Industry and Information Technology (from the 5th batch in 2018 to the 11th batch in 2018) and authors' recent source; ii) Data about Raw Material & Cell Components Producers is from Lüthje, Zhao, Wu, and Luo (2021) [4].

Local policy of battery clusters is normally included in local governments' overall strategic planning of EV industry, with geographically clearly defined plans of industrial clusters and financially detailed local support schemes. For example, "Zhejiang Automotive Industry High-quality Development Action Plan (2019-2022)" proposes to make Zhejiang a world-class automotive industry cluster by 2022. Zhejiang will focus on the construction of four major automobile industry clusters, relying on development zones (parks), high-tech parks, and characteristic towns that already have the basis, and promote the transformation and upgrading of internal combustion engine (ICE) vehicles and key components to smart vehicles and EVs. Zhejiang supports the establishment of an automobile industry fund, focusing on the R&D, production, and promotion and application of smart cars and new energy vehicles, and encourages financial institutions to provide credit, guarantee and other support for NEV projects. Fujian Province's "Modern Industrial System Construction and 100 Billion-Yuan-Level Industrial Clusters Promotion Plan" (2018-2020) identified 27 industrial clusters such as EV battery and new materials industry of rare earth and graphene, high-end equipment industry clusters, automobile industry clusters, and new chemical materials industry clusters as development priorities. Among them, EV power battery, rare earth, and graphene-based new material industry cluster construction plan contained five battery industrial parks and two graphene industrial parks. Guangdong Province's "Opinions on Accelerating the Innovation and Development of New Energy Automobile Industry" (2020) sets to promote the development of industrial agglomeration of NEV industrial clusters. Taking the Pearl River Delta for becoming the world leading base of complete EV, the policy aims to guide large-scale clustering of key parts and components production. During 2018 and 2020, facing more than 50% decline of national subsidies on EV purchase, Guangdong government subsidized the loan interest of local EV firms which produced and sold in the province but not yet received national purchase subsidies, up to 100 million Yuan per firm. The government also supported EV firms to issue special corporate bonds and green bonds. Besides using the provincial industrial development fund, Guangdong government also leveraged private and financial capital to support local EV firms.

Chinese local governments have full comprehension of the "EV battery industry chain" concept. They often identify all the stages from upstream material and components to downstream applications along the battery value chain, decide on which segment to develop as priority, then dedicate to solicit investment projects along the whole value chain. The approach is called "industry chain investment" in Chinese policy terms, meaning attracting firms to make investment to produce main battery products as well as supporting raw materials, auxiliary materials, parts, and packaging products to commonly construct a whole industry in one region. For example, in terms of developing complete EVs, Zhejiang province encourages OEMs to guide their suppliers to upgrade from ICE to EV models; it encourages pure EV firms to integrate electrification and digitalization to make high-end vehicle products. In terms of developing battery industry, Zhejiang supports developing technologies in fuel cell stacks, engines, and system integration. It supports firms to accelerate the development of fuel cell vehicles and hydrogen refueling stations. In order to promote the application of fuel cell vehicles, it plans to establish demonstration operations in urban public transport, logistics and transportation. Zhejiang also pushes to include recycling and reuse service system of nickel-metal hydride battery, lithium-ion battery, and fuel cell battery within battery clusters.

Similarly, Guangdong plans to build new clusters of EV in its eastern, western, and coastal areas, while expanding the production scale of EV batteries and key materials in the Pearl River Delta. In 2018, Jiangmen, a prefectural level city in the Pearl River Delta, successfully attracted twelve projects with 12-billion-yuan investment, covering cathode materials, anode materials, electrode materials, separators, equipment, energy storage batteries and other fields. Especially with the big investment in nickel-hydrogen battery cathode materials (spherical nickel hydroxide) for hybrid electric vehicles, Jiangmen is becoming the province's main production base for EV battery raw materials. The "industrial chain investment" approach results in emergence of local battery clusters with longer or shorter value chain, but always covering the main stages of EV battery industry. The small and medium sized Chinese battery firms in a cluster thus constitute relatively complete supply chain to OEMs, giving China localized advantages in EV battery materials, components, cells, packs, drive control and electrical systems, and even mechanical components. Furthermore, local governments emphasize "matching and connecting" battery supply firms within cluster and beyond cluster with OMEs as clients of supply chain. Zhejiang has established an incentive scheme to coordinate OEM and battery suppliers with purpose to enhance core component suppliers' ability. At provincial level, Guangdong organizes 1-2 so-called "matchmaking meetings" of new energy automobile industry every year to actively guide OEMs to cooperate with key parts and materials suppliers to promote upstream and downstream integration of EV value chain. Policy of "industrial chain investment" and "matchmaking meetings" generate multiplier effect and enhance comprehensive competitiveness of products, firms, and industries in the entire region.

Another emphasis of Chinese local cluster policy is on technology development and innovation. Local governments mainly use policy instrument of building "science and technology innovation platforms" such as public R&D centers, research institutes, technology alliances, and other forms of intermediary hybrid organizations to reach this goal [14] (pp.132-144). For example, Zhejiang province, like many EV clusters in China, focuses on developing pure electric and hydrogen fuel cell EVs. It identifies ten key technologies in the fields of long-life battery packs, fuel cell power systems, and their integration in complete vehicle. The targeted technologies include high-reliability membranes, catalysts and bipolar plates, hydrogen supply systems and key components, fuel cell system integration and optimization in complete car, and high-pressure hydrogen storage products and production technologies, etc. To develop these technologies but also other related technologies in energy-saving, solid-state batteries, electric engine, electric control, and autonomous driving, Zhejiang province built up a number of innovation platforms, including national and local joint engineering centers, national and provincial enterprise technology centers, engineering laboratories (engineering research centers), provincial (key) enterprise research institutes, innovation service complexes, and other related research and development organizations. The province also built some testing and standard service institutions to strengthen expertise in standards research, basic databases, complete vehicle and system safety of pure and hydrogen fuel cell EVs. A platform for professional talent incubation was also organized. Guangdong province has compiled technological roadmaps for pure electric vehicles, hydrogen fuel cell vehicles, and intelligent connected vehicles. The province also set up major technological research and development programs. From 2018 to 2020, 300 million yuan were allocated to R&D projects for key EV components such as electric motors, electronic controls and smart terminals, fuel cell systems and core components, battery electrolytes, anode and cathode materials, and other materials. Implementation policy measures were establishing 3-4 innovation platforms of NEV and key component each year. Financially, using its provincial industrial innovation platform funds, Guangdong subsidized the newly recognized national and provincial innovation platforms for launching. The province also coordinates OEMs, universities, scientific research institutes, and key component firms to form several industrial alliances for joint technology development in the fields of EV manufacturing, key component production, intelligent systems, and charging and replacement facilities.

At battery cluster level, the widely adopted policy approach by Chinese local governments is called the "five-one program", meaning each cluster shall construct one R&D institute, one testing & quality facility, one engineering center, one professional training center, and one venture capital fund. When more and more related and supportive firms join in to be closer to battery makers, the Chinese battery clusters progressively mature into "thick" battery manufacturing ecosystem [15,16]. With government policy of constructing innovation platforms, the Chinese battery clusters are rich of institutions, information, resources, and capabilities, very accessible and supportive to local firms. Therefore, battery cluster becomes in fact small-scaled sectoral innovation system which provides a local environment favorable to technological learning of cell design as well as production process improvement [17] (pp.247-264), two dimensions often intertwined. The reason that industrial cluster is important to mastering the technology of battery manufacturing is firstly because battery makers producing cells and packs provide in fact technical solutions to their clients, the OEMs. Connected to the raw material suppliers and cell component suppliers, battery makers integrate hardware parts and software battery management system into pack product and service to provide to OEMs. The

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working voltage of EV battery is 12V or 24V, but the working voltage of a single lithium-ion cell is 3.7V, so multiple cell units shall be connected in series to increase the voltage. However, it is difficult for the whole battery to have uniformly complete charging and discharging. If the single cells in multiple battery cell units and modules connected in series don't have uniformity and homogeneity in terms of quality traits, they become unbalanced in charge and discharge, and the whole battery pack will experience undercharge and over-discharge in usage. This situation will lead to drastic deterioration of battery performance which eventually causes the entire battery module to fail to work normally or even to be scrapped. Therefore, to solve the problem of battery durability and reliability, technical issues on materials, battery management systems, and mechanical processing shall be considered at the same time. It is often necessary for upstream firms of materials, management systems and other components to work together with midstream firms producing cell, module, and battery pack, forming an industrial cluster more conducive to technological progress and overall cost reduction. Within an industrial cluster, battery producers can easily contact lead users and obtain network support in terms of production capacity and site facility. Clusters create a kind of collective efficiency in stabilizing and homogenizing the quality of single cells integrated in cell units, modules, and packs, thus the quality of finished battery products to OEMs.

Chinese industrial clusters become the bedrocks of creation, growth, and market competitiveness of battery producers. Transforming small and medium sized firms in clusters to become specialized leading companies in national and global markets is both the effect and target of cluster policy. Chinese local governments carry out direct government-business cooperation with specific firms. Besides attracting foreign investment in EV industry, Zhejiang province has general policy to support leading domestic firms for mergers & acquisitions and strategic cooperation. The government of its capital city Hangzhou helped big firms such as Geely and Ali carry out acquisitions and cooperation in the global market. Fujian province works out specific support measures to help promising firms of battery packs, rare earth functional materials and application products, graphene, and other new materials, such as CATL, Dense Lion New Energy, Giant Power New Energy, Xiamen Tungsten Industrial Group, Shanshan Technology, and Jinlong Rare Earth. The fast-growing firms then not only build more parks and districts around the existing clusters to expand their production capacity, but also begin to invest vertically in other stages of the battery value chain, often located in other regions and provinces, even abroad. For example, CATL is headquartered in Ningde, a city in Fujian province. There it has constructed three manufacturing sites and then expanded to other two areas in the province. During 2018 and 2021, for expanding its lithium-ion phosphate battery production capacity, CATL made equity investment in four cathode material firms, two anode material firms, two mine extraction and sales firms, one manufacturing equipment firm, and one battery recycling firm, in different provinces. This geographic expansion contributes to the formation of more battery clusters in China, creating a dynamic interactive process among local government, large firms, and industrial clusters. Outside China, through six equity investments in American, Canadian, Australian, and African firms, CATL acquired access to metal mines such as lithium and copper.

With the emergence of specialized battery industrial clusters, often located outside traditional centers of car manufacturing but embedded in electronics manufacturing bases, China has formed the most complete supply chain of EV battery covering all relevant segments. Some battery firms having global competitiveness also emerge from clusters, well prepared for the future global division of labor. The cluster in Huizhou, focus of the next section, reflects these characteristics of industrial clusters as China's value chain advantage in EV batteries, but also more details about how such advantage is built at firm level.

2.2. The Case of EV Battery Cluster in Huizhou: From supply Chain to Industry Value Chain

In southern China, Guangdong Province has totally 26 EV battery firms which are geographically concentrated in its core region - Pearl River Delta. The Pearl River Delta, designated as a pilot region by the Chinese industrial master plan "Made in China 2025", is composed by nine prefecture-level cities such as Shenzhen, Guangzhou, Foshan, and Dongguan, and Huizhou, etc.

Together with Hong Kong and Macau, they constitute what is now defined as Guangdong-Hong Kong-Macau Great Bay Area in China. To understand the nature and dynamics of EV battery sector in China, our research takes the city of Huizhou as focus case. Neighboring Shenzhen and Dongguan, Huizhou is in east part of the Pearl River Delta and the fifth largest economy in the province with a GDP of 77.2 billion US dollars in 2021, to which its 2509 industrial firms contributed 52%. In EV battery sector, Huizhou has 10 firms, forming the largest local cluster with complete value chain in South China: BYD Corporation; Battery New Material; EVE Lithium Energy; Yineng Electronics; Desay Blue Micro New Energy; E-Power Energy; Sunwoda; Haopeng Technology; Yinghe Technology; and Kedali. Most of the firms are medium-sized and not well known externally, but they are hidden champions in domestic or world markets. In terms of installed batteries in Chinese EV market in 2019, BYD, EVE, and Sunwoda were respectively number 2, 6, and 9. E-Power was number 1 in bus market, Yinghe was number 1 in battery equipment market in China, and Kedali was number 1 in battery structural piece market in the world.

With the help of Huizhou municipal government, we were able to gain rare access to the field of cluster in Huizhou and carry out fact-to-face interviews with all these firms. Primary data were collected by three rounds of rigorous fieldwork in September 2016 (visit of 4 firms), May 2018 (visit of 9 firms), and August 2019 (visit of 10 firms). Each round of fieldwork consisted of manager interviews, factory visits, and focus group discussions. In-depth semi-structured interviews in each firm were conducted with top leaders and recorded with permission, lasting on average 2.5 hours, and touching all aspects of firm operation. Shop-floor visits were guided by managers with further explanation along production lines, testing labs, and control rooms. In the end of each week-long fieldwork, there was always focus group meetings organized by local government with participation of firm representatives and relevant officials. Each session of focus group lasted 2 hours with averagely 6 firms or government officials, Supplementary information regarding firms was then provided during these focus group discussions. Besides fact-to-face interviews and site visit, we also gathered and analyzed numerous documents such as firm internal reports, product catalogs and brochures, as well as government policy documents and strategic plans. The multiple sources of data, together with the transcripts of interviews and meetings allowed triangulation to increase the internal validity of our research. Finally, the multiple-source information of each firm was cross-checked and piled up in form of a case profile document with the same content structure. The analysis in following sections is based on the data from these case profiles.

Huizhou has a long history in consumer electronics manufacturing, which is one of the two pillar sectors, with petrochemical industry as the other. In 2019, 67% of Huizhou's manufacturing added value were created by so-called "advanced manufacturing firms", and 42% were created by "Hi-Tech manufacturing firms", both being mainly consumer electronics industry who has a distinct trajectory and constitutes a strong base of local network of suppliers since long time. In terms of market share in China, Huizhou has been number one for years in the field automotive on-board information service and products (in-car GPS). Its electronic & information technology sector was traditionally dominated by large State-owned enterprise or holdings groups, such TCL group, Desay group and Huayang group. But most local firms are small and medium-sized which complete the large manufacturing operations of leading firms. They are often parts and components suppliers in the upstream sections of electronics industry value chain, with low added value compared to OEM producers. They carry out little R&D activities and focus mainly on manufacturing of raw material, key component, modular parts, and semi-products, even some produce complete products. Even before 2010, many firms in Huizhou were already major producers of batteries for telecommunication, computer, cellphone, and other IT-related or digital products. These firms had been deeply involved in national and global competition in battery materials, cells, and cell components such as cathodes, anodes, and electrolytes. For many years, Huizhou positioned itself as "secondary city with strong industrial development orientation" and attracted a lot of investment spilled over from Shenzhen or Dongguan when the costs of land and labor became too high. Many private and foreign-invested firms relocated their plants and production facilities in Huizhou, thus geographically forming specialized clusters of supply chains serving extensively various industries.

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In recent years, with new investment, new industrial sectors emerge in Huizhou, especially those related to electronic and digital products, such as new energy vehicles & batteries, environmental protection, new energy equipment, new building materials, medicines, as well as the high-end advanced equipment, etc., giving Huizhou unique opportunities to deepen its manufacturing knowledge and assets in IT-related product battery supply chains.

But Huizhou's real jump into EV battery production was triggered and facilitated by the conjunction of a series of national industrial policies and local government cluster policies for developing EV battery sector. In EV sector, China's overall strategy was creating domestic market demand through subsidizing electric cars (New Energy Vehicles in official term) on one side and supporting domestic battery suppliers to carry out technological catch up and perform international competition on the other side. For this purpose, the National Development and Reform Commission published in 2011 the "Foreign Investment Guiding Catalog", stipulating that firms with foreign investment as major shareholder must not enter EV battery production. In the end of 2015, the Ministry of Industry and Information Technology introduced a catalogue of "Regulations on the Standards of Automotive Power Battery Industry" (commonly referred to as 'whitelist') including only battery models fully owned by domestic battery makers and chasing foreign competitors out of market. Though from 2018 the new "whitelist" begun to include Chinese joint ventures of foreign battery makers, this policy of infant industry protection did create a window period for Chinese battery firms to ratchet up quickly their production capacity and reach economies of scale. In 2016, the Ministry of Industry and Information Technology published "Norms and Conditions of Automobile Power Battery Sector" setting 8 Gwh (Giga Watt Hours) as sector entry barrier to promote expansion of production capacity. Later, Chinese government also used subsidy to push battery makers to increase the energy density, i.e., to upgrade battery product technology.

At local level, Huizhou government always takes automobile industry as policy priorities. Although long wishing but failing to attract major automobile OEM to invest, Huizhou successfully developed auto parts industry, composed of firms manufacturing power batteries, automotive electronics, auto parts, wire harnesses, and engines, etc. Its total output value of automobile industry in 2015 was more than 35 billion Yuan. When the EV market demand begun to surge up with national subsidy policy, Huizhou government quickly turned to give full support to EV-battery supply chain development in leveraging its long experience and strong foundation in consumer electronic components production. The battery cluster policy has a long list, including massive financial support from provincial government; permission of establishment of an industrial park and various related supportive policies; developing a complete local industrial chain to create conditions for the migration of corporate headquarters from Shenzhen to Huizhou; providing talent and financial support for production expansion; speeding up project approval and simplify approval procedures; providing financial support for technology research and development, and encouraging enterprises to expand R&D centers; attracting OEMs to set up subsidiaries; tax incentives for innovative start-ups; and financial subsidies and loan facilities, etc.

Incentivized by policy support, numerous firms in Huizhou with consumer electronics backgrounds transformed themselves to EV battery producers or suppliers by investing in new manufacturing equipment and production lines. In a short time, Huizhou emerged as an important industrial cluster specialized in EV battery manufacturing both domestically and internationally. Vehicle-scale power battery value chain is long and composed of many specialized segments. The upstream segments include raw materials and precursors extracted from mines and cell components manufacturing which cover mainly cathodes (metals), anodes (graphite), electrolytes, and separators. Battery manufacturing and assembling are middle segments, including cell production, module assembly, battery management system (BMS), battery packs, thermal management system, etc. Related and supportive products such as battery structural frames, precision parts, and manufacturing equipment can also be regarded as specialized middle segments. The downstream segments are customized applications and installations of finished power batteries in various markets, such as electric vehicles, movable energy storages, and electric grids, etc. Downstream segments also include battery recharging, reuse, and recycling, etc.

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In Huizhou, as illustrated in Table 2, from upstream through middle stream to downstream of battery value chain, almost every specialized stage or segment is occupied by some local manufacturing firms, with cell production and pack assembly as the focal and key segments. For example, BYD, EVE and EPOWER are all leading firms producing cells and parks in their respect target markets. EVE manufactures battery cells and packs and applies battery products to EV power train and energy storage systems. EPOWER explores to use new cathode materials to substitute imports and develops battery management systems with its own property rights. Its products are used to supply hybrid power for usual buses. As for BYD, it had been long time in battery production for consumer electronics before entering in the EV industry. BYD was originally a supplier of Li-batteries for computers and smartphones to Foxconn and other large electronics manufacturers. Now it has been fully engaged in all segments of battery value chain, supply batteries for its own branded electric cars and energy storage applications. These fast growing and innovative local firms have made Huizhou one of the largest EV battery production clusters in the Pearl River Delta and even in China. It means that even at local level, the industrial cluster contains a rather complete EV battery value chain which can provide one-stop power solution to OEM car makers.

Table 2. Battery firms and industry value chain in Huizhou cluster.

Segments of EV battery value chain	Raw materials and components						Battery manufacturing and assembling			Related and supportive industries		Battery applications and usages		
	Mining ore	Anode material	Cathode material	Electrolyte	Separator	Other (adhesive, binder, etc.)	Cells and modules	BMS	Packs	Structural components (tabs, insulator, containers, etc.)	Equipment for cell and pack production	Complete electric vehicles (passenger and commercial)	Stationary Energy storages	Reuse and recycling
Battery NM	■	■		■		■								
BYD			■	■	■		■	■	■	■		■	■	■
EVE Lithium Energy							■	■	■				■	■
Sunwoda							■	■	■					■
E-Power Energy							■	■	■					■
Haopeng Technology			■				■							■
Desay Blue Micro New Energy								■	■					
Yinghe Technology											■			
Kedali Precision										■				
Yineng Electronics								■	■					

This kind of battery cluster in Huizhou covering almost the whole value chain segments creates an environment embodying firm competitiveness [18] (pp.849) or ecosystem favorable to cooperative interactions among local players [11]. With government support policies and accessible capitals and institutions, firms in Huizhou can reduce collectively their production costs. Geographic concentration and proximity enhance their exchange of information, resources, and capabilities. It is easier for local firms to learn from each other and for OEM to contact the whole supply chain, thus forming local production networks. Industrial cluster attracts more specialized firms to come and invest. Kedali, the precision structural frame maker, said it would have never come to Huizhou if there had no such a specialized cluster of battery. Like in many other Chinese places, battery cluster in Huizhou has become the bedrock to the creation, business growth, and market competitiveness of regional economy.

3. The Making of Competitive Advantage: Core Competency of Chinese EV Battery Firms

In strategic management theory, core competency is defined as a harmonized combination of multiple capabilities, resources, and skills that distinguish a firm from its competitors in the marketplace [9] (pp.79-91) [19] (pp.111-125). Contrary to approach of Porter's five competitive forces, which takes external environment as key factor to influence firms, the concept of core competency focuses on firms' internal capabilities. Numerous authors consider core competency as the source of competitive advantage of an individual firm [9(pp.79-91),10(pp.38-49),20,21(pp.173-189)]. The value chain structure of Huizhou battery cluster shows clearly that its industry-level competitive advantage is concentrated in the key business segments of cells, BMS, and packs. A deep dive within each firm's value chain reveals that this advantage is rooted in manufacturing activity and the corresponding production capacity in growth, which constitute firm's most crucial primary activities and bases for development of core and expanded products for end users. Local EV battery firms have developed the entire supply chain and aggressively scaled up their production capacity by limiting market access to the world's leading producers on their advantage. In fact, these technological capabilities of mass manufacturing and increasing rapidly production capacity are becoming "core competency" for local EV battery producers in China. Since the whole EV battery industry is still in emerging stage and firms are all "newcomers", their core competency is considered as a process which delivers higher and unique value for customer compared to other primary or support activities within firm's value chain and compared to foreign firms. This process in common for the Chinese battery firms is manufacturing activity in large scale, resulting from pragmatic technological learning carried out at the level of workshop floor.

3.1. Mass Manufacturing: The Nature of Core Competency

A firm's value chain is composed of both primary activities such as logistics, operation, production, marketing and sales, service, and support activities such as procurement, human resources, and technology development [22]. In a relatively short period of time, the EV battery firms in Huizhou cluster have considerably developed all the value chain activities and been particularly dynamic in forming capabilities and resources in production, sales, and technology development. Table 3 describes their main characteristics.

Table 3. Key value chain activities of battery firms in Huizhou.

Firm	Main products	Production and operation	Market and sales	Technology development
Battery NM	- mining ore - anode material - electrolyte - adhesive - binder.	- Reached mass-production and is expanding production capacity;	- Domestic mainstream customers; - Develop materials	- Developed a silicon carbon anode material; - The R&D base is headquartered in Shenzhen;

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<table>
<tr><td></td><td></td><td>- Automated production lines, import of key equipment.</td><td>together with customers;
- Traditional cathode and anode materials markets are saturated, so firm develops new segments.</td><td>- Development of comprehensive lithium battery technology solutions (material application)</td></tr>
<tr><td>BYD</td><td>- cathode material, electrolyte
- battery pack cover
- lithium-ion cells (LFP, NCA, and NMC)
- packs of prismatic design
- own BMS
- own brand electric cars and buses</td><td rowspan="4">- Mass production and large-scale expansion of production capacity (totally 12.1 Gwh/year);
- Realized fully automatic intelligent production line for cell production;
- Semi-automatic, fully automated, and intelligent manufacturing lines are used according to different products. But less automatic production line for pouch packs;
- The front-end equipment is mostly imported, and the battery pack assembly line and logistics line at the back end are developed by firms in-house.</td><td rowspan="4">- Market segments include EV power train, energy storage, and power storage of small vehicles
- Supply cells to the producers for their battery modules and battery packs assembly, some of them are local producers;
- Packs with BMS are supplied to domestic mainstream customers and international mainstream customers (OEM);
- Emphasize on rapid response to customer needs;
- Set up specialized professional force for after-sales service;
- The impact of subsidy-reduction policy on the market demand was relatively big. Firms generally felt the pressure of cost killing</td><td>-“Blade” battery design of pack
- Research is mainly to extend battery life and increase energy density</td></tr>
<tr><td>EVE Lithium Energy</td><td>- lithium-ion cells (LCO, NMC, and LFP)
- packs of cylindrical, prismatic, and pouch designs
- own BMS</td><td>Routine development of cell design to increase energy density</td></tr>
<tr><td>Sunwoda</td><td>- lithium-ion cells (NCA and NMC)
- packs of prismatic and pouch designs
- own BMS</td><td>Battery pack system design optimization</td></tr>
<tr><td>E-Power Energy</td><td>- lithium-ion cells (LMO)
- pouch pack specially designed for electric bus power train
- own BMS</td><td>-Circuit system redesign
-Using active liquid cooling technology for battery systems
-R&D associated with battery material research
-Research backup from Beijing</td></tr>
</table>

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			from clients (OEM).	Polytechnic University
Haopeng Technology	- cathode precursor - lithium-ion cells of NCA			Some technology development but admits that there is a gap between its overall technological level with Japanese and Korean companies'
Yineng Electronics	- pouch pack for EV power train - BMS			No significant technology development
Desay Blue Micro New Energy	- parks of prismatic and cylindrical designs - after 2018, focus on BMS (including BMU and BCU)			Iterative development of software systems, multiple sets of BMS
Yinghe Technology	- front-end and back-end equipment for lithium-ion battery production, especially machines for production steps of laser cutting/ slitting, winder/ calendaring, electrode shaping - equipment IT system such as MES - complete intelligent assembly line, etc.	- Has reached mass-production and is expanding production capacity; - The overall level of automation of equipment production is not very high; - Non-standard equipment products must be assembled by hand; - Precision parts processing with automation.	- Domestic mainstream customers; - Products are customized for customers; - Provide a lot of training support to customers, similar to robot manufacturers.	- The only firm manufacturing intelligent production line solution for lithium battery production (turnkey project); - Develop own industry-specific manufacturing execution system (MES); - Develop "digital factory" concept
Kedali Precision	- metal structural parts for electric box - metal structural parts	- Plans to produce 30 million sets per year; it has reached mass production and is expanding its	- Serves domestic mainstream customers; - The national market share is 50%, and the	- Take use of experience in the mold industry since many years to carry out

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	for car batteries and storages	production capacity; - Main equipment is imported. - Equipped with automated production line. - Pre-purchase of equipment suppliers' several years of production capacity	global market share is 20%; - Keep up with the needs of mainstream car companies (OEM) and able to supply to OEM directly.	product process innovation; - Develop precision components for intelligent vehicle control systems

Note: LFP= Lithium-iron phosphate; LMO= Lithium-manganese-oxide; NCA= Lithium-nickel-cobalt-aluminum; NMC= Lithium-nickel- manganese- cobalt; LCO= Lithium-cobalt-oxide (cells for smartphones, laptops, and cameras, etc.); BMS= Battery Management System; BMU= Battery Management Unit; BCU= Battery Control Unit.

In the upstream segments of the battery industry chain, i.e., battery materials, equipment and structural parts, local firms in Huizhou are all market champions. In the downstream segments, i.e., the products of battery cells, battery packs, and battery management systems, firms in Huizhou have also entered the supply system of well-known domestic OEMs. Totally these EV components and parts producers achieved sales revenue of 12.45 billion Yuan in 2017, selling more than 800,000 units of products. They produce all three forms or pack designs of final battery products: cylindrical, prismatic, and pouch designs. Prismatic and pouch designs are the mainstream products in Chinese markets. The pouch design is most adaptable to installation space in vehicles. In the field of product technology, the electrochemistry of EV battery is the same as the battery for consumer electronics products (MP3, cell phones, laptops). NMC (Lithium-nickel- manganese- cobalt) and LFP (Lithium-iron phosphate) are the two dominant Lithium-ion cell electrochemical formulas. NMC is higher in energy density but more expensive, while LFP is less performant in energy density but cheap in price. Battery producers in Huizhou made little radical breakthrough in cell chemistry based on fundamental research. Their product innovation is either in sourcing more efficient materials from better material suppliers to make incremental progress of product quality, or in redesigning battery pack architecture, like the "blade battery" design of BYD. This was also the general situation at national level. According to the International Patent Classification in 2017, the global top ten companies in EV battery patents were all from Japan, the United States, South Korea, and Germany, with a total of 3278 patents. Chinese battery firms focused on developing manufacturing and engineering process within the existing technology paradigm of Lithium-ion battery.

It is in this field of manufacturing and production that the battery firms in Huizhou built their strength and reached a world level. Especially for those who produce battery cells, modules, and packs, they have already formed a kind of distinctive mass manufacturing capability of quality battery products and gained substantial market share in competition. Their production capability in very high volume has become competitive advantage of Chinese EV battery sector and is reflected in three aspects:

Huge production capacity realized by reliable mass manufacturing and production engineering activities. Even in 2017, the Huizhou cluster's EV battery annual production capacity reached 12.1 Gwh (Giga Watt Hours) which meant 196, 700 sets of EV battery parks, almost 7% of national production capacity, and the eventual annual output of 31, 800 sets. BYD, Sunwoda, EVE Lithium, E-Power Energy, Yineng Electronics, and Haopeng Technology have all transformed to automatic large-scale manufacturing. The production capacity of each firm continued to increase rapidly. For example, in 2019, BYD reached 40 Gwh, EVE 20 Gwh, and E-Power 2.8 Gwh.

Large amount of fixed assets formation through massive and rapid investment in new equipment and production lines. Through years of experience, battery firms in Huizhou have developed strong capabilities in production projects investment. They are quick and skillful in every stage of investment, including capacity planning, facilities building, production engineering, scaling up, as well as implementing the advanced manufacturing system with newest equipment imported from different sources. In 2009, in order to commercialize its lithium-ion batteries, BYD already built its first fully automatic LFP production line. Its mass production of EVs started in 2013-2014 and the production capacity was only 2 Gwh. But within four years, its battery production capacity reached 16 Gwh. Now BYD workshop of battery production is totally automatic: car welding is done by robots, and mechanic manipulators are used to make metal exterior parts. EVE begun its lithium-ion EV battery projects in 2014, an investment of 600 million Yuan to build a fully automatic 18650 power battery factory with an annual output of 1 Gwh. In 2015, it built a production line with the highest level of automation for cylindrical battery in China. Then from early 2016 to the end of 2017, EVE invested 5 billion Yuan to reach the scale of 9 Gwh and sales of 6 billion Yuan. As for E-Power, it invested 200 million Yuan in equipment, including 150 million for production use and 20 million for R&D. The key production equipment and process equipment are almost all imported, especially from Japan. Desay Blue Micro New Energy invested 100 million Yuan during 2015 to 2016 to build two automatic production lines of BMS. Now it has totally three BMS production lines with an annual output of 200,000 sets and five automatic lines for pack assembly within a 10,000-square-meter workshop. As a structural part producer, Kedali’s production lines are also highly automatic. Equipment is imported from Japan, South Korea, and Germany. For cleaning and circulating discharges, all equipment is imported. For the shell pulling machine and high-speed stamping equipment imported from Japan, Kedali even bought out in advance all the anticipated output of the Japanese supplier in the next 4 years, thus monopolizing the market order.

Continuous practices in production optimization, quality improvement, and cost control. In EV battery production, good quality means basically homogeneity among cells which requires stability and standardization of manufacturing processes. After production lines are built up, local firms in Huizhou also engage in continuous efforts regarding production process to increase efficiency, improve quality, and reduce costs. For example, in order to benchmark the production technology of Panasonic, EVE invited Panasonic's expert team to guide product design and production line construction. Its internal "high-quality programs" emphasized on strict quality control and high success rate in final inspection. A better quality of EV battery often means product adaptation, adjustment, and redesign according to changes of customer needs. In reference to the existing safety parameters, the optimization of battery quality often lies on increasing the volume lightweight and energy density of battery modules which can directly reduce battery costs. Besides using the learning curve effect, battery firms in Huizhou also widely use “machines to replace manpower”. Production costs are well controlled thanks to decreasing number of workers in production line.

The above mass manufacturing capabilities of quality battery products constitute the core competency of Chinese local battery firms. Theoretically, a firm’s core competency shall make a significant contribution to the perceived benefits of end product, provide potential access to a wide variety of market segments, and difficult to be imitated by competitors [9] (pp.79-91). The mass manufacturing capabilities of battery firms at this stage meet all these criteria.

First, as the battery is 35% of EV cost, customers need reliable and durable battery for EV. Standardized mass production process can guarantee stable supply of cells, modules, packs, the integrated BMS as well as thermal control system, so deliver unique values to EV makers. Based on huge production capacity, modularization and adopting chemical formula of LFP give Chinese battery firms competitive advantage in price, while some new product design such as Cell-To-Pack also increases battery energy density, giving customer more value in quality.

Secondly, this mass manufacturing capability of lithium-ion battery of all capacities can be applied to diverse end markets beyond electric cars, such as smart grid, urban transportation, solar panels, and movable storages. Even within electric vehicle segment, lithium-ion battery is applied to buses, trucks, even urban trams for public sectors. Before entering the EV passenger car industry, BYD supplied lithium batteries and metallic accessories to branded consumer electronics firms, personal computer manufacturers, and mobile phone makers, such as Foxconn. In 2003, in using its core technological competency in batteries, BYD entered the electric passenger car industry, through acquiring a domestic branded car firm. BYD is active in other energy segments than EV powertrain, such as solar panels, LED and energy storage, accounting for 20% of total revenue. EVE also produce various energy storage systems, such as rooftop energy absorption, power banks, or emergency power sources, etc.

Finally, the mass manufacturing as core competency of Chinese battery firms is more about scale and process than about product and technological innovation, constructing some barriers to imitation. Although the lithium-ion battery chemistry is not revolutionary new technology, making it at a large size with large volume to reach large energy capacity requires considerable investments to purchase new and automatic equipment for production, controlling, and testing. At present, there is not much technological difference between cell design of various firms, competition is based on mastering of large-scale production and manufacturing. Chinese firms formed core assets through huge capital expenditure within a relatively short period. Purchasing and using the most advanced manufacturing equipment from various sources also provide an opportunity for Chinese firms to learn skills and accumulate experience in implementing large scale production process to EV battery making. Related to Made in China 2025, battery production has seen a significant push for digital automation. For Chinese firms, automation is mostly introduced to improve quality standard. These know-hows, information, and skills about production engineering, system integration and quality control are then reinforced by firms' external environment which provide accesses to various supplies inside or outside cluster. The time-consuming experience and specialized cluster environment are difficult to be replicated elsewhere.

3.2. Technological Learning: The Building of Core Competency

Mass manufacturing as core competency of Chinese battery firms represented not simply large production capacity, it had some technological substance, i.e., it was a kind of technological capability [23] (pp.820-841). By nature or origin, technological capability was obtained through a process of "technological learning", which was in general the way firms obtained knowledge from the environment, the way this knowledge was managed and diffused into the organization, as well as the way knowledge coming from the suppliers or the clients was processed and transformed into new capabilities [24] (pp.189-205). The so-called technological capability was embodied in the collective process of research, implementation, exploration and development of technologies; it was therefore synonymous with technological learning [25] (pp.495-521). C. K. Prahalad and Gary Hamel (1990)[9](pp.79-91) also pointed out that core competencies are the "collective learning across the corporation" and often developed through the process of continuous improvements over period rather than simply large production capacity. There are numerous approaches of technological learning, but the dominant approaches adopted by Chinese battery firms were based on their manufacturing practice at factory level: learning-by-doing, by-using, and by-interacting, corresponding to the DUI mode in innovation system literature [26] (pp.747-756).

The first approach used by Chinese battery firms was "learning-by-using". As mentioned earlier, a major technological challenge of mass production of EV battery was not about the cell chemistry redesign, but the much larger size of compound pack to be installed in vehicles. Lithium-ion batteries, first commercialized by Sony for use in consumer electronics in 1991, now dominate power batteries for EV use. The compound electrode and electrolyte structure of lithium-ion batteries are similar to alkaline batteries that have been used to power consumer electronics for decades. But lithium-ion batteries are lighter and significantly more energy-dense than their alkaline counterparts, so suitable for EV applications through enlarging the battery size to supply enough power [12]. Initially, EV-grade lithium-ion batteries faced several constraints when produced in large volume. The production shall be localized near EV OEMs due to high costs of transportation and custom duties. The low standardization degree of manufacturing process led to unstable quality of cells and packs, especially for pouch and cylindrical batteries. The most difficult part came from manufacturing process. EV battery making contains several steps. First, the unitary cells are assembled into small modules one by one. The combination of cells includes series and parallel. The series combination is to increase the voltage, and the parallel is to increase the energy intensity. Single cells are welded into small modules, which are then connected to form a large battery system. The battery system is connected to the battery management system (BMS) through many pressure sensors and wires to monitor the voltage and temperature of the battery. This integrated battery system to be installed in EV is what is termed as "pack". During the whole production process, key technical tasks are to keep the unitary cells have the exact same good quality level, otherwise a single cell with different quality level will quickly exhaust the whole battery in usage. Production process of EV batteries thus shall be much more stable and consistent than for small batteries for IT products such as smartphones or laptops.

Chinese battery firms solved the problem of transition to standardized volume production of large-size batteries by investing heavily in substantial automation and most advanced equipment, especially in the mechanical parts of cell production process and materials handling.

(1) In the workshops, standard procedures were automized to improve quality, such as using ultrasonic welding machine to connect battery components. For Battery NM Company, their production process of silicon-carbonized anode materials was customized and lack of standardization and stability, requiring using very precision equipment. To reduce manual operations, Battery NM invested 10 million Yuan to import automatic equipment from Japan. Then the firm learnt from using this most advanced equipment to import more equipment from Japan, Germany, and other countries. They debugged and installed equipment for transportation pipelines and three-dimensional warehouses, now trying to make the whole production line fully automated. Like Battery NM, many Chinese battery firms got used to integration, installation, operation, and maintenance of equipment from different countries and regions. They accumulated knowledge of engineering and automation to achieve process standardization.

(2) In parallel with the importation of equipment, Chinese battery firms also tried to introduce intelligent manufacturing system or *industrie 4.0* to support the equipment operation with new digital technologies such as big data and industrial internet of things (IIOT). There were national and local policy programs to back up such kind of industrial and technological upgrading. For example, BYD realized full automation of its front production processes through importing cell-making equipment such as feeder, coating machine, and winding machine from Japan and South Korea. From 2008 to 2016, through three major programs of technological transformation, EVE upgraded its EV lithium-ion battery production line from manual to automatic then to the so-called industrie 4.0 level. The main expenditure of programs were capital goods.

(3) Based on learning of purchased equipment, battery firms began to adapt machinery or even develop their own equipment, especially for the conventional customized processes. BYD set up a special manufacturing plant to develop its own equipment for the end processes in pack assembly line. Much of EVE's automation equipment was also developed by the firm itself. In 2015, it took a year for EVE to successfully develop the first automatic production line for cylindrical batteries. For that automatic line, EVE applied for a total of 20 patents (7 invention patents and 13 utility model patents, of which 7 utility model patents have been authorized). Automation doubled the production capacity, reduced 80 manpower, increased the average product qualification rate from 89.8% to 92%, and dropped the manufacturing cost by 21.76%.

The second technological learning approach of Chinese battery firms was "learning-by-doing" or by-producing. In terms of product, the technological trajectory of lithium-ion battery cell is rather science-based [27] (pp.388). Japanese industry was the first to find a realistic alternative to lead-acid batteries, developing the first lithium-ion batteries in late 1980s. Knowledge about battery cell design is a combination of chemical, electrochemical, and mechanic knowledge on materials, electronics, electricity, and mechanics, etc. Cell design has to consider simultaneously the different aspects of material, mechanical processing, and digital management of battery, etc. There exist many alternative EV energy storage technologies which are always R&D targets of leading firms, such as solid-state battery, hydrogen and fuel cells, "flow" batteries that utilize zinc, and other chemistries. But the electrochemistry of lithium-ion EV batteries has derived a considerable first mover advantage, thanks to East Asian lithium-ion battery producers, notably Chinese makers that were able to make massive and rapid investments in production capacity to accrue the bulk of the benefits from economies of scale and learning-by-doing. Although the lithium-ion battery seems to lock the EV industry into its technological trajectory as dominant cell design, the sibling chemistries with lithium-ion family, including NCA, NMC, LMO, LFP, LTO and LCO, each has its own specific composition of chemicals and are different in energy density, safety, and reliability.

China's technological choice of lithium-ion battery was greatly influenced by the choice of EV types. In China, new entrants especially those had background from IT industry all chose pure battery electric vehicles, while traditional OEMs mainly chose hybrid electric vehicles. As for plug-in hybrid electric vehicles, it was required that the battery independently shall support minimum 50 Km recharge mileage in China. As for fuel-cell vehicles, the power system was always equipped with a battery. Finally, pure battery vehicles became the mainstream EV in Chinese market and got government subsidies. But all these technological choices created excessive market demands of lithium-ion batteries and boosted the emergence of EV battery industry in China. For cell chemistry, at the beginning Chinese battery firms chose mainly NMC, greatly increasing the energy intensity, but expensive because it used precious and non-ferrous metals. But with continuous adjustment of cell ratios and improvement of materials, recently many firms shifted to LFP which dropped the cost significantly. In 2021, the installation of LFP even outpaced NMC.

As lithium-ion battery becomes dominant cell design for EV, further technological opportunities are to be found in how to produce batteries in large volume with good quality, i.e., manufacturing processes. Besides the challenge of quality stability, performance reliability, and consistency among cells in mass production as mentioned above, quite a lot of EV battery process technology is know-how, skills, experience, and implicit knowledge by nature, without strong legal protection of intellectual property. The knowledge sources are always related to production activities, including product and process engineering, equipment operation and maintenance, work-flow arrangement, product testing, assembling, quality control, and cell components purchase, etc. EV battery manufacturing process can be improved through incremental integration of practical knowledge from workshop floor into better components, machinery, and pack assembly. Thus, the appropriate ways of obtaining and assimilating this implicit knowledge are just practicing production process, trying, drawing lessons, and accumulating experiences as much as possible, activities that are often referred to as 'learning by doing'. The dynamic development of Chinese battery firms, especially production capacity expansion, moving to new sites of production, and introducing new equipment provide repetitive occasions for intensive technological learning by producing. For example, EVE increased drastically its production capacity and automatized the assembly lines. During the process, the firm obtained valuable production and engineering know-how. Its engineers relied on accumulated experience to set technical parameters for large-scale operation. For cell production, E-Power used mainly domestic equipment, such as slicing and tableting machines. Its specific cell structure for pouch pack made it difficult to achieve complete production automation, although the entire factory was designed according to assembly line. Many processes rely on manual operations by workers. In Yinghe Technology, the processing of precision parts was automated, especially by using robotic arms imported from Japan which accounted for about 10%-20% of equipment investment. However, since much of its own equipment is non-standardized and the equipment it produced for client were always customized, the overall degree of automation was not very high. Equipment production required a lot of manual assembly, so Yinghe Technology emphasized on workforce training and talent development. In 2016, Yinghe Technology created its own university, composed of a management school, a professional college, and a mechanic-electric school. The core technical ability of Kedali originated from the professional mold industry founded in 2009. The company kept development molds even after focusing on producing precision parts for EV batteries. Now Kedali has purchased complete sets of equipment, but mold development and part production still rely much on the accumulated technical know-how of professionals from mold industry.

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Though China did not have world-level revolutionary technological breakthrough in lithium-ion cell design or material innovation, the accumulation of manufacturing experience and diffusion of best practices in engineering, design and distribution brought significant "learning curve" effect, which linked the rate of price declines to the cumulative volume of battery packs deployed on the market. It is estimated that there was an 18% cost reduction for every doubling of battery production capacity [4]. Another effect was efficiency increase. After the battery was produced, there was usually a static depolarization process to test the battery self-discharge and identify defective cells. For this process, some Chinese battery firms reduced the time from 10 days to 6 days by repeatedly practicing and establishing large-scale test centers with charging and discharging test channels that could test more than 1,000 batteries at the same time.[1]

Mass production of quality goods also implied search for technological information, negotiation of technology, and establishing linkages with ecosystem actors such as suppliers, customers, distributors, technical centers, and even research institutes, etc. Thus, the third way that Chinese local battery firms master manufacturing was "learning-by-interacting", including "learning from market", "learning from alliance", and "learning by monitoring" supply chains, etc. By tracking needs of lead users and constantly adjusting cell chemistry and pack structure to be more aligned with those of the leading OEM producers, Chinese EV battery producers became better manufacturers, more and more able to achieve the quality standards their customers demanded. When EVE became a potential supplier of BMW and entered into "apprentice" stage, it also received very detailed requirement containing quality and technical standards for installing batteries in specific models. When selling materials to CATL, Battery NM first gave samples for testing. Then there was exchange between technical personnel of the two sides. After the order was placed, the quality departments conducted joint quality audit, and then the regular communication between production staff started. CATL normally sent personnel to conduct one or two audits every year, and the sales staff of Battery NM also had to pay a return visit. Samsung SDI was the most important customer of Desay Blue Micro New Energy. In order to participate in Samsung's battery supply to Volkswagen's small batch car models on the MQL/MQB platform and bid for models on the new MEB platform, Desay Blue Micro New Energy elaborated R&D plan jointly with Samsung and adopted Design of Experiments method to develop customized BMS. E-Power mainly supplied public bus companies pouch packs. In order to track the end users' information better and to identify possible modifications and improvements to products, E-Power signed after-sales agreements on quality assurance with users, set up a dedicated after-sales service and maintenance team, and installed an alarm system in each battery. The alarm system enabled the firm to obtain timely feedback on technical issues related to usage and monitor and respond to customer needs.

Battery firms also learnt new technical knowledge from setting up alliance and partnerships with car makers and key component suppliers. Each year, BYD invited Japanese experts to give training on issues like lightweight cars and organized seminars on electronics topics such as molds. In 2010, BYD set up a 50/50 joint venture with Daimler AG to develop electric vehicles. BYD was responsible for battery, electric engine, and electriccontrol, while Daimler AG was responsible for

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[1] Although effects of learning and economies of scale often overlap in practice, they have clear own definitions in economic theory. Economies of scale are cost decreases that result from expanding production. Economies of scale are frequently found in industries that require large capital expenditures on plant and equipment, or the establishment of a large infrastructure prior to the ability to begin providing service. While learning curve benefits can be attributed to improvements in labor efficiency as workers' dexterity improves, standardization, specialization and work method improvements, improved use of tools and equipment, product redesigns to improve assembly efficiency and productivity, material substitutions and more efficient use of inputs, and a shared experience effect when multiple products share usage of common resources [28]. Both effects can be found in Chinese battery firms.

complete vehicle design, molds, and safety, areas where BYD wanted to learn. Since the EV battery value chain contains numerous specialized producers for materials, components, battery management systems, cells, modules and battery packs, an industrial cluster with complete value chain can greatly facilitate cooperation among upstream and downstream firms and is ideal for local learning by interacting with all kinds of suppliers. Knowledge and experience can easily be diffused within cluster.

The technological learning paths of Chinese firms reveal to some degree the emerging technological trajectory of lithium-ion EV batteries. In battery value chain, cell and pack producers play a central role. By supplying lithium-ion battery packs to EV car makers, they are in fact system integrators or solution providers through cooperating with various technical partners and specialized suppliers of raw materials, components, parts, hardware, and software. Due to its electric-chemical nature, product innovation and process innovation are intertwined and inseparable for EV battery. Process innovation is often incremental and embedded in key manufacturing activities including product detailed design, testing, engineering design, and quality control, which have high technical requirements for equipment and input materials. Therefore, in addition to external technology development partners, technological upgrading of battery firms depends heavily on internal experience and know-how accumulated during its own processes of technical engineering and mass production. After production reaches a certain scale, smooth mass manufacturing can permit feedback loop of sufficient and professional information from customers to product design, then to testing and engineering design. The information on needs of users, especially of lead users, can inspire battery firms to develop new technologies to match the user's requirements.

If there exists some technological foundation of the competitive advantage of Chinese battery firms, it is their shop-floor technological learning which occurred simultaneously when firms undertook explosive mass manufacturing and production capacity expansion. From a macro perspective of EV battery sector in China, innovation happens not mainly at product level, but more in production process. Traditionally, indigenous Chinese suppliers have been very good in manufacturing needed parts and components to foreign multinational companies, then enter into newly emerging and more sophisticated foreign multinationals' supply chains [29] (pp.109-125). Electrification of automobile powertrain has its technological roots in battery electrochemistry, a cross field of chemistry, electronics, electricity, materials, and mechanics, which is not included in the mainstream technological domains of old automobile industry and its supply chains. But the EV battery needed by Chinese and foreign OEMs was not a product innovation in strict technological sense, and the Chinese battery makers caught such a surging business opportunity and quickly applied and adapted their mass manufacturing capabilities to the new field. Mass manufacturing and technological learning are the two sides of the same coin of their core competency. And after achieving certain technological level of mass production process, Chinese firms allocated more resources to tackle new product or component development, such as silicon-carbon anode material, high nickel cathode material, coating die of battery equipment, cell-to-pack design, and even solid-state battery, etc. Many also consolidated their cooperation with research institutes and academia in search of more radical technological breakthroughs. For example, E-Power cooperated with Beijing Polytechnic University in research of optimizing anode materials and using ceramic separator to replace imported expensive materials. The firm also invented a new "active liquid cooling technology" to dispatch the heat inside pack.

4. Discussion and Implications: The Futures of EV Battery and Automobile Sectors

Our discovery on the nature and characteristics of core competency of indigenous Chinese battery firms provides a vantage point to understand some broader issues regarding global and Chinese automobile industry under electrification. Both vertical integration and segment specialization strategies of battery firms are based on competency development logic. The emergence of Chinese battery firms is restructuring the traditional automobile value chain. Core competency in battery mass manufacturing also has implications on the competitiveness of Chinese electric vehicle makers in the long run.

4.1. Implications to Battery Makers

By exploiting core competency, Chinese battery firms adopt either "vertical integration" strategy or "segment specialization" strategy for further growth, which in turn widens or deepens the obtained core competency. The strategy of "vertical integration" is represented by cell and pack makers like BYD, EVE, Sunwoda, and Haopeng Technology. The "segment specialization" strategy is practiced by smaller pack makers like E-Power and Desay Blue Micro New Energy, and specialized product suppliers like Battery NM, Yinghe Technology, and Kedali.

The strategy of vertical integration is controlling the whole EV battery value chain as much as possible, from upstream activities of mining, materials processing, cell component making, through cell, module, BMS production, to downstream pack assembling and applications in various sectors [7] (pp.178-201). Battery makers may even downstream integrate further other key electric components supply, e.g., electric engine and electronic control system, etc. to supply to OEM, or engage directly in electric car production and assembly. Based on their core technology expertise in cell production, both EVE and Sunwoda position themselves as integrated new energy system provider. In its early development, EVE tried to enter directly into EV rental business. Now it is searching to acquire some material production. Sunwoda is carrying out full value chain engagement. For raw materials and cell components, it signs strategic cooperation with key suppliers. For cell production, BMS, pack assembly, electric motor and control system, it owns and operates the activities directly. Sunwoda also tries to engage in EV making, EV car-sharing and public transportation, and battery recycling through equity investment or technical service contract. The famous and typical example of vertical integration is BYD's strategy. BYD integrated almost all segments of EV battery value chain, but its original involvement was battery production. Before BYD started complete electric car production, it was a lithium-ion battery and part supplier to consumer electronics producers. In 2008, BYD purchased a semi-conductor manufacturing company Ningbo Zhongwei for more than 200 million Yuan, therefore acquired the competency to develop and produce electric engines. Today, BYD owns its own battery factories producing from cells, modules, BMS, to packs and supplies for its own car assembly. Recently the firm acquired upstream producers of battery raw materials, cell components, and car parts. It outsources very few components and materials, just supplementary materials like adhesives for batteries.

Standardized mass manufacturing of battery packs itself contains integrating cells, modules, and BMS. It requires stable and consistent supply of raw materials, cell components, and other relevant parts. These supplies must conform to the quality and technical demands of battery makers. The prices of these supplies must be under control because OEM producers always pass their cost pressure on battery firms who have to squeeze production costs. At the same time, the accumulated technological knowledge from mass production process of EV battery allows them to possess more knowledge about upstream and downstream activities and firms in battery value chain. Exploiting their core competency in making cells, modules, BMS, and packs, battery firms can have an advantage in merger, acquisition, and investment in other firms backward or forward. Vertical integration thus widens this core manufacturing competency by extending to upstream and downstream fields. It is the reason why, even regarded as the most integrated EV company, BYD positions itself strategically as an "energy corporation", meaning that its business covers new energy vehicles, mobile energy storage and other segments, but always based on using lithium-ion battery technology originated from consumer electronics battery.

Meanwhile, mastering process technology of standardized manufacturing creates favorable conditions for undertaking design improvement, new product development, and more R&D, activities which can differentiate firms from competitors in a limited niche market. Compared to the popular verticalization strategy by large battery makers, segment specialization is the choice of most local firms in Huizhou, since they are in upstream segment or small-sized. Battery NM is in raw material and cell component production. It chooses to become more specialized in extracting and refining anode materials and try to hold leading position in anode material technology in China. Desay Blue New Energy has decided to abandon its pack assembly line in order to concentrate on BMS production. Now the firm is a niche market specialist in BMS. Both Kedali and Yinghe

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Technology choose to keep their positions as “hidden champions” in their specific markets. Kedali has become a first-tier supplier of lithium battery precision structural parts and other metal parts for EV. Yinghe Technology has developed integrated equipment system for the whole process of lithium-ion battery manufacturing, including all equipment for front-end electrode equipment, middle-stage cell assembly, and rear-end cell finishing. E-Power stays in the segment of pouch batteries for electric bus and specialized vehicles. Its differentiation strategy is to become a specialized supplier based on engineering activities, by providing customized battery to hybrid EV. These local small firms take use of the accumulated experience and specialized know-how to develop differentiated product lines targeting higher quality and value, and become more innovative players in specific supply chain segment. They are not only reinforcing existing manufacturing capacity, but also deepening it.

In one word, core competency is of high relevance to Chinese battery firms’ growth strategy in the future. Theoretically, the degree of vertical integration is determined by the rate of technological progress, not the rate of growth of the market. When the density of information is great, when the function and the market of the product are yet ill defined, and when the degree of standardization/modularization of components and parts is low, firms have to rely on in-house supply. As the product and its production process become better defined and more standardized, external suppliers emerge and the original firm can specialize on whatever aspect of the product or process it deems most strategic [30] (pp.93-118). In the short run, due to the absence of shareholders asking for a maximum profit, Chinese battery makers will overstretch durably in many segments of battery value chain. The present trend of verticalization in battery value chain will continue with large Chinese firms trying to grab a larger share of the battery value chain by expanding upstream and downstream. But in the long run, they may have to refocus on their initial core competencies – cell design and manufacturing. Being originally a battery maker for consumer electronics, BYD has already had some signs of “refocusing” on its core competency of making batteries. It positions itself as an “energy company”, not an “EV company”. From 2018, it begun to supply BYD battery packs to other OEMs, not limiting to its own use. BYD emphasizes that it is by nature an energy corporation based on battery technology, opening to supply other OEMs by the BYD batteries from 2018. This will lead to a consolidation with conglomerates larger than they already are. Number of battery makers will be reduced with industrial concentration. Even when these big firms do not have the financial means to mobilize enough money in all the segments in which they are present, they will invest an increasing amount of money in R&D.

4.2. Implications to Car Makers

The concept of core competency also has strategic implications to car makers, especially to those transforming from ICE (internal combustion engine) to EV.

The value chain of ICE automobile sector contains segments of material and parts, tier 1 suppliers, OEMs, dealership and distribution, aftersales service and usage. Globalized production networks of ICE cars, with a hierarchical supplier structure, are dominated and controlled by multinational brand-name carmakers from Europe, US and Japan pyramids (commonly known as the ‘Toyota model’). EV emergence, or electrification, digitalization, AI and internet connection (intelligent cockpit and internet connected vehicles) combined, has vertically disintegrated this ICE automobile sector into distinctive but related subsectors or industries, each having its own value chain and specialization process: battery manufacturing, powertrain and driving system, car software, automotive semiconductor, EV design and assembly, EV contract manufacturing, digital and intelligent manufacturing, and even smart mobility service, etc. Global supply chain is no longer a top-down structure, but multidimensional in the sense of distributed centers of innovation and industrial players controlling different segments. The global carmakers are no longer the undisputed leaders in the automotive sector [31] (pp.80-98).

Among these specialized industries, EV battery is by far the most developed with a relatively complete value chain from raw material, to cell components, battery cell, BMS, pack, applications, recharging, and recycling, etc., each having a tendency to form its own ecosystem. Battery technologies are important for cars and battery has a lion share in car cost. Dominating the automobile market means controlling the battery value chain [1] (pp.156-177). In this sense, Chinese battery makers are reshuffling the hierarchy of power within global automobile production networks, thus upending the automobile global value chain from a below position. In face of the rising power of battery makers, should car makers explore new competency in battery making? Should battery making be part of their new core competency? And how far should car makers integrate the battery value chain? Is battery materials knowledge equally important as their manufacturing and cost control capabilities, and electric car design know-how?

It makes sense for large car makers to integrate the competency of cells manufacturing as well as cell design in-house [32] (pp.229-246). But by now, the OEMs' integration of battery making can only be described as "partial". The main approach of car makers is to have long-terms and large-scale contracts with battery makers to guarantee the procurement and avoid shortages. Another increasingly adopted approach is to set up green-field or brown-field joint-ventures with battery makers to manufacture batteries near their main assembly factories. Fewer move into cells manufacturing themselves or even into mining and refining.

The reasons of partial integration lie on technological competency. Battery making itself is becoming an independent industry and contains many segments. First, as shown by Huizhou cluster, Chinese battery producers' core competency regards essentially cell chemistry, cell manufacturing, and the process of integrating cells, modules, BMS, and TMS, etc. into battery packs or systems. Relevant technologies also cover electric drive, electrical control system, power electronics and electric motor control. Battery knowledge is about electrochemical chemicals, relatively new and interdisciplinary, different from ICE auto parts and beyond the exclusive control of ICE carmakers. Secondly, Chinese battery makers' core competency is in fact strong manufacturing and cost control based on volume production. This manufacturing technology is mainly learnt through experience accumulation at workshop level. In lack of accumulated competency in mass manufacturing, many car makers have abandoned battery cell or pack business, turning to get involved in BMS, electric drives, power electronic components, and other specific fields, or limit their own production activities to the assembly of battery packs into car frames Even for pack assembly, packaging cells into modules and battery packs require developing necessary software, manufacturing battery control systems, thermal control, chassis, and electric engine, etc., a whole bunch of new competences.

In other specialized industries other than EV battery, car makers have to decide what new competency they need to build. The choice depends on prediction of future structure of automobile sector as well as battery industry.

Within battery industry, verticalization by big producers and specialization by smaller ones both consolidate their core competencies within the boundary of battery industry. If the vertical integration continues, car makers will face bigger battery makers who adopt modular mass manufacturing to hold dominant positions in production capacity, battery delivery volume, delivery time, and vehicle installation volume. The OME-supplier relationship thus will be open based on standardization and modularization, instead of captive interaction.

On the other level, the most likely structure of the whole automobile or EV sector is that its value chain continues to be divided and specialized into several modularized segments: standardized battery pack and skid-mounted battery swap module, standardized frame module, and electronic control and autonomous driving module, etc. Each of these modules will have large-scale manufacturers. The fragmented sector is controlled respectively by branded battery integrators who control battery value chain, car assemblers who may be contract manufacturers, driving system integrators who control powertrain electronics and high-performance semiconductors, etc. Such an EV sector in the future will be similar to the electronics and other high-tech industries, such as mobile phone or IT products, where industry-wide modularization of core components is under "open-but-owned" standards, and product innovation is separated from manufacturing, called *Wintelism*.

An EV version of *Wintelism* will be characterized by mass production of battery makers as core component suppliers controlling technology and production, and having both R&D and manufacturing competencies, complemented by rise of independent makers of digital drive trains or software suppliers [1] (pp.121-136). This is a gigantic "massive modular ecosystem" [33]. Car makers

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have to find a position between these two ends, an alternative strategy to the highly integrated model of BYD and Tesla.[2]

4.3. Implications to Local Governments

In catching the opportunity of EV boom, Chinese local battery firms are rapidly mastering lithium battery manufacturing, becoming either component specialist or system integrator. In the long run, the above future scenario of EV sector restructuring calls for local battery makers to build a kind of core competency to maintain flexibility of technological options and openness of industrial ecosystem. This kind of flexible specialization competency contains broad R&D capacities, highly developed manufacturing services, and co-innovation ability with downstream applications [34] (pp.308-329). It can only be built in local clusters which, with appropriate government policy, can evolve in industrial ecosystems.

The case of Huizhou illustrates how industry value chain was developed in a Chinese industrial cluster. Huizhou local government identified different segments along the battery value chain and set up specialized industrial parks for each segment. For example, government attracted battery material firms to settle in the material industrial park, set up one-stop professional service system for vehicle batteries, and built battery-related microelectronics industrial cluster. Policies and programs were set up to promote an inter-firm cooperation, new product development, and intelligent manufacturing, etc. As a system integrator, BYD played a role of sticking to peripheral suppliers. Battery cell and pack producers cooperated with firms in related industries, such as processing equipment manufacturers and material manufacturers. They also established cooperative relations with customers, actively participated in their product development, and jointly carried out research on materials and BMS. Their technological learning improved production efficiency and strengthened quality management.

For the future, local government shall have ecosystem policy to transform the battery manufacturing clusters to more advanced ecosystems of production and innovation. Flexible specialized clusters in European regions like Baden-Wuerttemberg or "Third-Italy" provides a reference model for small and medium-sized battery makers [35] (pp.354). These clusters are characterized by diversified industrial structure, specialized small and medium sized firms cooperating closely with each other, not face to face competition based on price and cost, flexible flow of talents, high skill workers, and adaptive education system. Flexible specialization is inherent to IoT or industry 4.0 technologies and creates opportunities of decentralization of car manufacturing directed to the needs of local markets, mobility systems and communities. It is time for local governments to form pertinent ecosystems through technology policy, industrial policy, urban policy, labor policy, financial policy, and infrastructure investment, etc., to leverage flexible specialization potential of battery makers.

5. Conclusions

China has a leading position in electric car sector, which is backed up by its powerful development of lithium-ion battery industry. Overall, the Chinese EV battery industry has enormous production capacity and formed a complete value chain from upstream materials production to middle steam manufacturing of cells, modules, BMS, and packs, and to the downstream applications, mainly in EV but also in various other fields, such as grid storages, lightings, solar energy, movable storages, etc. From a national economy perspective, China now is possible to have this distinctive energy storage industry applicable to many other sectors and the battery firms as EV battery suppliers have formed a relatively independent and specialized industry in face of the auto OEMs

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[2] Even the most vertically integrated firms such as BYD who adopted from the very beginning an approach of 'total autarky' are still dependent on (global) partnerships and hence do not signal the return to massive quasi-autarkic conglomerates. BYD will focus on one chunk eventually, if not completely only focusing on one chunk in the EV sector.

and car assemblers who are traditionally the main bones of automobile industry. From a sector perspective, due to the electrification of cars, battery producers, as well as other firms in the battery and electric engine supply chain, are becoming very significant players in the automotive sector. This is maybe the biggest change of automobile sectoral structure.

China's value chain advantage of battery industry has its roots in firms' core competency, which consists of massive manufacturing of stable quality EV battery cells, modules, and packs, and rapid scaling up of production capacity through aggressive fixed assets investment. Although the core competency results finally in production capacity and the competitive price of batteries, its formation experiences a learning process of manufacturing technologies. During mass production, Chinese firms actively engage in accumulating know-hows from experience, learning using advanced equipment, learning from clients and alliance, and learning to monitoring supply chains. They have built up an EV battery manufacturing system combined of advanced equipment, cell designs, production engineering plans, production procedures and organizations, and workers' skills and know-how, etc. In this sense, the core competency of Chinese battery makers is also technological by nature. In addition to the learning process, the formation of core competency is also facilitated by the local specialized battery cluster where firms are located. In fact, the Chinese battery clusters are characterized by strong local government support and battery value chain structure inside which provide a favorable immediate environment for technological learning in firms.

The core competency of Chinese battery firms is the foundation of their strategic moves in value chain, vertical integration or segment specialization. The future of EV and battery industrial structure is also influenced by the distribution situation of battery core competency between battery manufacturers and OEMs. Can government take the core competency issue as a focal point when they make decisions regarding battery segment, value chain, cluster, and firms, and will it do so in practice?

Mass manufacturing of battery as core competency makes China hold the biggest value share in global EV sector. But excessive manufacturing expansion also creates problems of capacity surplus, fierce competition, declining margin, and pollution, etc. [36]. Will the core competency of Chinese firms continue to make China global battery sourcing base to global car industry? Will it be learnt by other firms including OEM and become conventional and basic capabilities of EV industry in the future? All these questions are to be answered by further research.

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