Ministry of Foreign Affairs

Opportunities and challenges for companies in the Netherlands in rapidly growing battery and e-mobility industry

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Executive Summary

South Korea has distinguished itself in the industry of battery for electric vehicles. The K-trio battery makers (LG Energy Solution, SK On, and Samsung SDI) have already taken up over one third of the entire battery production in the world. In terms of production capacity, only the Chinese manufacturers are regarded as comparable competitors. As of 2021, the combined global market share of K-trio was over 50%, except the Chinese market. To be specific, in Europe and the US where a rapid market growth is forecasted, the three Korean battery manufacturers are expected to continuously reinforce their market dominance. Particularly in the US, since the enactment of the Inflation Reduction Act (IRA), it is not an exaggeration to say that the Chinese companies are literally ruled out of the competition, leading to a reasonable speculation that the K-trio are highly likely to solidify their leading position in the US market. With the increasing supply from the K-trio companies, those related with cathode and anode materials are expected to significantly benefit from such increase and market expansion. More investments from those companies are also anticipated to meet such a high demand for their products.

[K-trio overview of capacity and supply chain]

	LG Energy Solution	**Samsung SDI**	**SK ON**
Production capacity by 2025 (as of 2022)	550GWh (196 GWh, Global #2)	113.8GWh (54GWh, Global #6)	220GWh (77GWh, Global #5)
Global Production lines	Korea, U.S., China, Indonesia, Poland	Korea, U.S., China, Malaysia, Hungary, Austria (Pack)	Korea, U.S., Hungary, Turkey
JV with Global OEM	GM (U.S.), Hyundai (Indonesia), Honda (U.S.), Stellantis (U.S.) Hyundai (tbd, U.S.), Renault-Nissan (tbd, U.S.)	Stellantis (U.S.)	Ford (U.S.), BAIC (China), Hyundai (tbd, U.S.)
Suppliers			
- Cathode	LG Chem, Nichia, B&M, Umicore, Posco Chem.	Umicore, SDI, L&F, EcoproBM, BASF-Toda	EcoproBM, L&F, Easpring, Reshine
- Anode	Posco Chem., Mitsubishi, BTR	Mitsubishi, BTR, NOVONIX	Posco Chem., BTR
- Separator	Toray, Senior, SEMCORP	Asahi Kasei, Toray	SK IET
- Electrolyte	Enchem, Guotai Huarong, Ube	Central Glass, Mitsubishi Chem., Panax E-tec	Enchem, Solbrain
- Cu foil	Iljin Materials (Lotte), SKC, Doosan Solus, Watson	Iljin Materials, CCP, Watson, SKC	Watson, SKC
- Equipment	CIS, PNT, Yunsung F&C, Hana Technology, OST, Innometry, etc.	TSI, Hanwha Momentum, CIS, Hana Technology, Innometry, etc.	PNT, Yunsung F&C, Wonik PNE, Innometry, etc.
Recycling (metal extraction)	Sungeel hightech, Sebit chem., EcoPro CnG, Posco-GS EcoMaterials, Posco-HY Clean Metal, SK Ecoplant		

This report provides an outlook for electric vehicles and battery markets till 2030 and the global position taken by the K-trio battery makers. It also introduces the basic development roadmap for battery technology presented by the top 3 Korean battery manufacturers. The report identifies the current issues in the battery industry and possible countermeasures. Technology-wise, this report covers the entire ecosystem of battery industry and lifecycle of battery cells: from the 4 major components for battery such as cathode material; module and pack; equipment for battery production; next-generation battery such as all-solid-state battery; second-use and recycling; and charger/charging infrastructure. In doing so, the report specifies the technology status of today, future development directions, and imminent issues that industry players have been trying to address.

[Pain points of Korean battery industry and strategy to overcome]

Issues	Threat	How to overcome
Market demand	- Price pressure (annual avg. 6% decrease) - Rapid production capacity building	- Process technology development - LFP cathode
Fire issue	- NCM cathode	- Solid electrolyte (Solid State Battery) - BMS/System design - LFP cathode
Supply chain disruption	- Dependent on Chinese material (90% of cathode raw material) - Policies: IRA (US),	- Expanding/strengthening international partnership - Recycling battery - Localizing material production/processing
Sustainability issue (ESG)	- RMA (EU incl. Carbon tariff, Due Diligence Requirements through the Supply Chain, etc.) - RE100	- Decarbonizing process - Local sourcing - Renewable energy sourcing

The Netherlands, known for highly advanced semiconductor equipment and maritime industry, has been pushing forward its state-led project to enter the secondary battery industry based on capabilities and resources found in the country. There are approximately 80 companies and organizations in the country working in relation to battery system, second-use/recycling, and battery materials. In order to accelerate the development of the secondary battery industry in the Netherlands, one of the prior tasks is to build a cooperative relation with players in the battery industry of Korea who have been successfully leading the global battery industry. To come up with cooperative strategies for the Dutch companies, this project first studied the strong points that those Dutch companies have. Based on the study, we identified direction in which the Dutch companies should proceed to successfully foster their own secondary battery industry. In doing so, we also came up with solutions to take advantage of the strengths that those Dutch companies have.

The Netherlands is located in Europe where the battery and electric vehicle markets have been rapidly growing. Even the Korean battery manufacturers have continuously built new production lines or expanded the existing ones in Europe. As a large volume of battery is manufactured and consumed in Europe, the second-use/recycling industry is expected to grow after a while at a pace that is similar to that of the battery industry. While there are no big-name companies yet in the second-use/recycling industry, recycling/reuse technology has a great potential for further development and innovation. As many Korean companies have been striving for expanding their business realms in cooperation with the European companies, there should be a promising possibility in promoting cooperation between the Dutch and the Korean companies in the second-use/recycling sector.

Furthermore, the ALD technology, in which the Netherlands has strength, can be considered as a potential solution for some of the current issues that the Korean battery makers have tried to deal with. The technology is also expected to have a great potential in application to cathode and anode materials as well as all-solid-state battery.

[SWOT analysis of the Dutch battery/e-mobility business Targeting Korean market]

Strength - Niche player with disruptive technologies (deposition process, etc.) and e-mobility sectors (maritime, heavy duty and personal mobilities)	**Weakness** - Weak Li-ion cell manufacturing capacity - Almost no big OEM - Physical/mental distance
Opportunity - Material/process R&D and commercialization	**Threat**

partnership (next-gen battery and recycling)	- Low visibility in Korean market
- Battery application partnership: e-bike, maritime	

1.Electric Vehicles & Battery Market

1.1 Development of Electric Vehicles

Since the Paris Agreement in 2015, countries in the world have promoted electric vehicles to fulfill the greenhouse gas emission reduction goal agreed in the international society. <Table 1> provides a brief summary of regulations and government subsidy policy established in major regions.

Table 1 Regulations and Subsidy Policy in Regions

Region	Regulations	Subsidy Policy
China	- Corporate Average Fuel Consumption - NEV Policy (Sale of electric vehicles of a specified portion)	- Subsidy support (year 2022) - Benefit provided when purchasing a license plate - Quota allocated for each city/province
Europe	- Regulations on carbon emission and currently in place and to be strengthened on a yearly basis	- Subsidy support (subsidy amount vary depending on circumstances in each country)
US	- Corporate Average Fuel Economy	- Subsidy was granted to a limited number of vehicles, but recently with the enactment of Inflation Regulation Act, the government subsidy policy has been integrated.

The regulations and subsidy policies in different regions stated above seem to be quite similar to each other, but there are certainly slight differences between the regions when it comes to their positions to foster and strengthen the EV-related industries. In China, their policy focused on fostering China to become a leader in the automotive industry in accordance with the so-called reform and opening-up policy led by Den Xiaoping. It must have considered the fact that it would be difficult for them to catch up advanced car makers in the existing internal combustion engine (ICE) market and that it should effectively reduce fine dusts in major Chinese cities like Beijing.

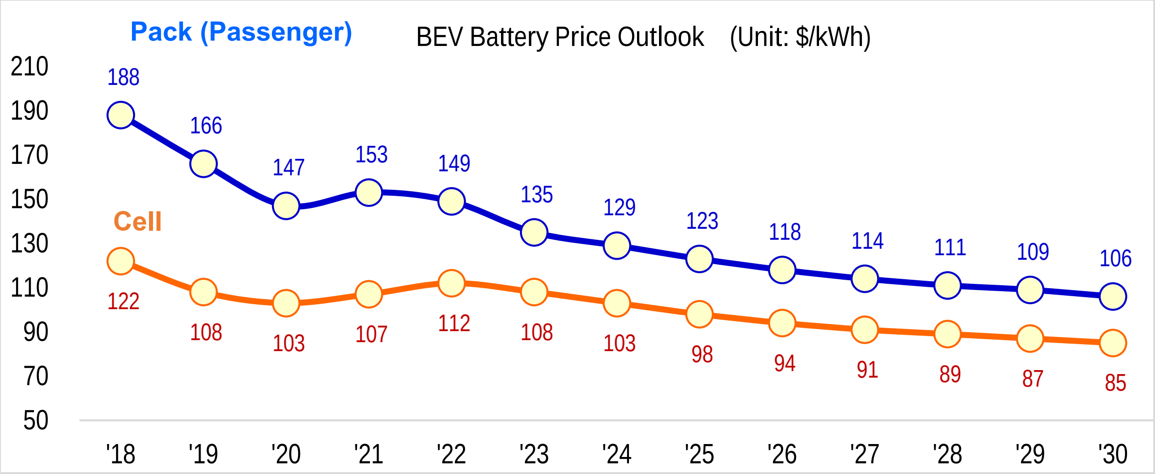
In Europe, car makers must have reached a conclusion that they cannot address the environment issues by any other means than electric vehicles and choosing electric vehicles are almost directly linked to their survival in the market. The sales proportion of diesel-engine vehicles in Europe has been actually dropping, and some of the European cities started to review a complete ban on diesel-engine vehicles or already prepared for the actual implementation.

In the US, centered on California where the CAFÉ (Corporate Average Fuel Economy) has been continuously in operation, the EV market has been actively formed. The number of states adopting the CAFÉ system has increased to 10 or more. Recently, the Biden administration has enacted the Inflation Regulation Act to keep the industrial security in electric vehicle and battery sectors. The US has been focusing on the establishment of EV eco-system as a pivot of the national economy and the prevention of Chinese companies from prospering in the US economy.

The regulations and subsidy system that have been continuously implemented for the past 10 years have led to the birth of star companies such as BYD in China and Tesla in the US. Tesla is an electric vehicle company which has drawn attention from the world as its market capitalization ranked top among the global car makers as of July 2020.

One of the importation factors to consider when it comes to the growth of electric vehicle is the development of battery technology. **Figure 1** below presents the forecast on average production cost of battery cell and pack used for electric vehicles (BEV _ based on passenger vehicle) by year. Due to the recent increase in raw material price, the price of battery cell is expected to rise for a certain period of time, but, propped up with technical development and economy of scale, it is forecasted to maintain a steady, downward pace in the mid-to-long term.

Figure 1. EV Battery Cell/Pack Production Cost Forecast[1]



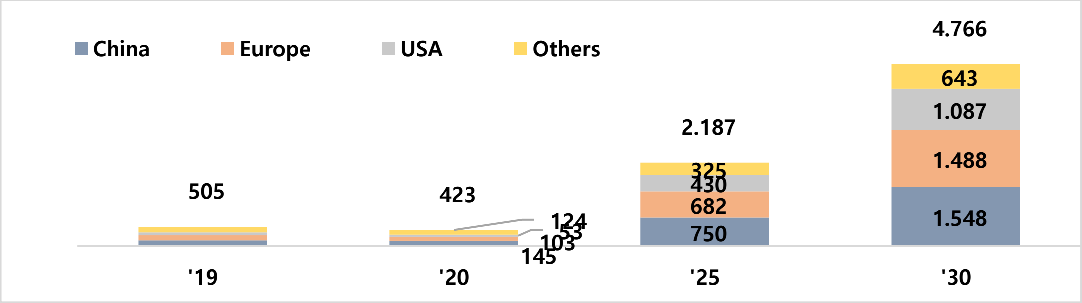
(Unit for Y axis: $/kWh)

Figure 1 reflects a rapid surge in raw material price to the battery production cost caused by the Russia-Ukraine War. Those factors leading to raw material price increase are expected to have less influences in around 2024, with their impacts dropping as low as the level of 2020. After 2024, the production cost is forecasted to continuously drop and, in 2030, the average production cost of cell is projected to reach the level of 85$/kWh. The battery cell price, at which the prices of electric vehicle and ICE vehicle become equal, is estimated to be approximately 100$/kWh. The price parity is expected to be achieved after 2024.

In addition, from 2015 to 2020, the energy density per cell weight – regarded one of the important performance factors in battery – has been greatly improved from around 200 to 300 Wh/kg (SNE, 2020). Cell price reduction and energy density improvement are assumed to be mainly driven by the enhancement of battery cathode usage (more nickel used) and the improvement of productivity based on mass production.

Figure 2. EV Sales Forecast (Region/Year)

(10 thousand units)



To forecast the sales volume of electric vehicles, the production plans and future strategies of car makers were first studied. Usually, approximately 3 years before a vehicle is launched, the development of vehicle begins, and contracts for key components like battery are made about 2 or 3 years before the launch. We came up with the EV sales forecast by year which reflects surveyed data. The forecast result is presented in Figure 2.

The average annual growth rate of electric vehicles is projected to be 23% from 2019 to 2030. The amount of battery required is estimated to be the average annual growth rate of 35%. This is because, rather than HEV with a smaller battery capacity (approximately 1.2 kWh), BEV (approximately 54 kWh/unit) seems to be a leading model in the market. Region-wise, the European market is expected to continuously expand and have the market at the scale similar to that of China in 2030. A decline in the EV sales in 2020 compared to 2019 was due to the COVID 19 pandemic.

Table 2 shows the estimated sales of electric vehicle by global top 5 OEMs whose EV production and sales expansion are forecasted to be significant.

Table 2. Global Top 5 Electric Passenger Car (Forecast till 2030)

(Unit: 10,000 units)

OEM	'19	'20	'24	'25	'26	'29	'30
VW	23	28	207	265	315	533	639
Toyota	169	117	275	306	338	479	547
Renault-Nissan	39	38	165	201	235	381	450
Tesla	37	30	117	143	169	283	337
Hyundai Kia	32	28	125	153	177	275	319
Total	299	242	889	1,068	1,233	1,951	2,292

In 2025, the number of electric passenger vehicles sold is expected to exceed 10 million units. VW, whose annual average growth rate is forecasted to be over 38%, is anticipated to take the top position, outrunning Toyota in 2027. Toyota, who previously focused on HEV, is expected to expand its realm into PHEV and BEV from 2020. Renault-Nissan, Hyundai-Kia and Tesla are all forecasted to see the annual average growth of 20% or higher. Other than these companies, GM, Honda, PSA, Geely and FCA are regarded as companies to actively increase the number of electric vehicles sold down the road.

Other than electric passenger vehicles, pick-up trucks and small trucks categorized as commercial vehicle are expected to have more diverse models released starting from 2022, possibly leading to the expansion of sales. One of the representative models in the commercial vehicle category is Cyber Truck by Tesla, which is anticipated to have an outstanding growth mainly in the US and Europe.

1.2 Battery Market

Together with the growth of EV market, the use of battery required for electric vehicles has significantly increased and the line expansion has been actively conducted to raise the production capabilities of battery manufacturers. As of 2020, the battery production bases were mainly located in China, South Korea, and Japan.

Recently, investments in battery production line have been jointly made with OEMs who will be using batteries for their car making. Joint investment (including independent investment made by OEM) or investment by battery makers based on the supply contracts with OEMs is prevalent in the industry. The production base and battery investment have been mostly concentrated in China but continuously expanded to the US and Europe. As of 2030, China is expected to account for 56%; Europe 32%; and the

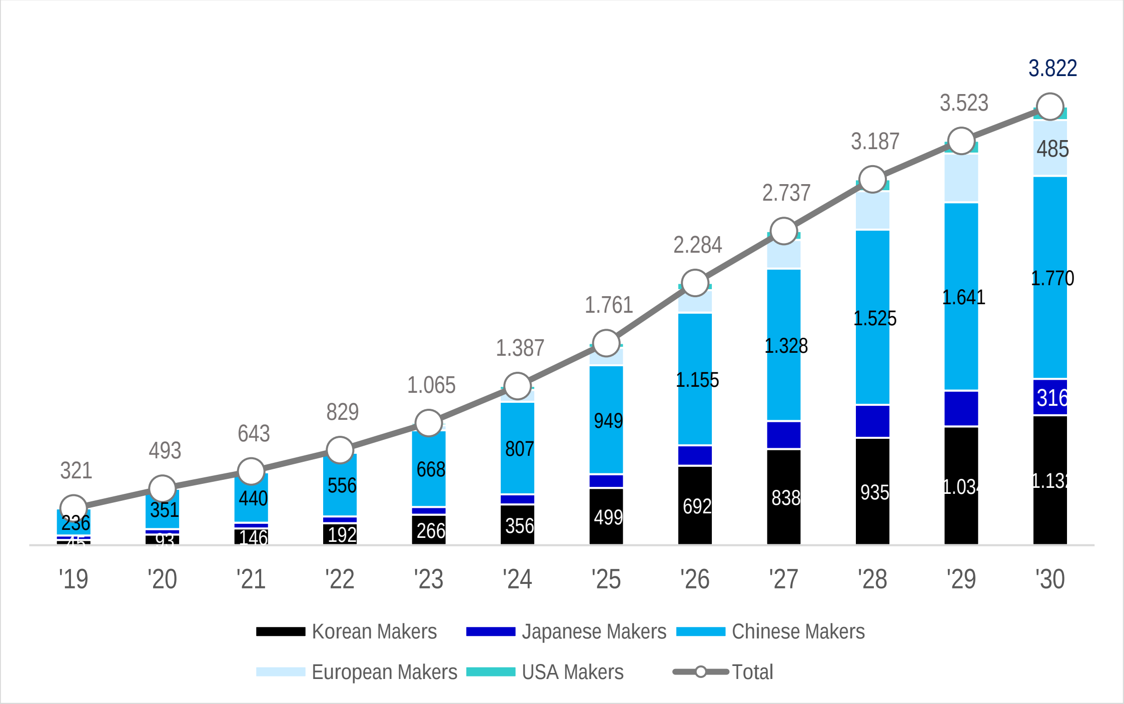
US 9%. On the other hand, Japan and Korea who took up 3% by each in 2020 are expected to see a slight decline in their shares down to 2% and 1% respectively in 2030.

By company, the Korean and Chinese makers are forecasted to have the average annual growth rate of 23%, and their combined shares are expected to reach 87% as of 2030. On the other hand, the Japanese companies have kept their conservative stance on capacity expansion, while companies in the EU are more probable to actively enter the battery business.

Major players in the market are LG Energy Solution, Samsung SDI and SK On in South Korea; CATL, BYD, Lishen, Guoxuan, EVE, and CALB in China. Newly rising battery suppliers in Europe would be Northvolt, Tera-E, Saft and VW.

Figure 3 shows the battery supply forecast by battery makers in different regions. The production capacity, reflecting the actual battery production capacity (approx. 70% of design capacity), is expected to reach 3,822 GWh in 2030.

Figure 3. Battery Supply Forecast by Battery Makers in Regions



Even if several battery makers increase their production capacity, from the mid- to long-term perspective of supply and demand, it is expected that battery supply and demand will not be smooth from 2024. If we match car companies that need batteries with battery companies that supply batteries, it is expected that the battery supply and demand situation may become more difficult. In other words, battery capacity reflects all battery investment plans around the world, including the capacity of Chinese battery makers. From the perspective of global automakers, except for excellent battery makers such as CATL, BYD, and Guoxuan, given stable quality assurance, systematic production methods and development capabilities, not many options are left when it comes to choosing suitable battery makers. Although automakers are expected to make efforts to secure batteries through participating in equity and shareholding, it is expected that biased focus toward proven battery makers will become more obvious over time.

According to our analysis on the battery consumption by region and the supply-demand balance of production bases, for a certain period of time, surplus batteries in China are expected to move to Europe and the US. Companies that benefit from this will be blue-chip battery makers such as LGES(Energy Solution), Samsung SDI, SK On, CATL and BYD. Chinese battery makers are also likely to change their production bases to Europe rather than investing in China. The recently enacted IRA in the US is fundamentally making it difficult for Chinese battery makers to invest in the US, and in Europe, legislation for raw material management similar to the US IRA has been reviewed. Given these circumstances, Korean companies are highly likely to benefit more from the global market situations down the road.

2. Roadmap for Battery and Technology

2.1 Three Korean Battery Players

As shown in Figure 4 and Table 3, the three Korean battery companies are expanding their production bases to Europe and the United States. In the case of Europe, the proportion of production capacity as of 2020 is 32%, and through continuous capacity expansion, it can be expected to increase by 49% in 2030. It has been already explained that increase in battery production capacity is achieved through cooperation such as automakers' pre-orders or joint ventures. Samsung SDI signed an agreement to supply batteries for BMW and Volvo electric trucks. In addition, it is expected to promote capacity expansion through a joint venture with Stellantis. LGES is responding proactively to capacity expansion, and its Plant 1 in Wrocław, Poland, has about 22 battery production lines (approximately 50 GWh) as of the end of 2019. In addition, LGES is expanding its second battery plant in Poland in line with the growth of the European market, and the necessary funds were supported by the European Investment Bank. The Wrocław plant aims to expand by 100GWh. In particular, LGES is actively participating in JVs. It has been increasing its production capacity through joint ventures with Geely, Hyundai/Kia Motors, and GM. Their cooperation is expected to further expand. SK On is growing its production capacity centered on major electric vehicle markets. It is intensively expanding its production lines in the US, Poland and China.

Figure 4 Capacity Expansion Outlook for K-trio Battery Makers (Unit: GWh)

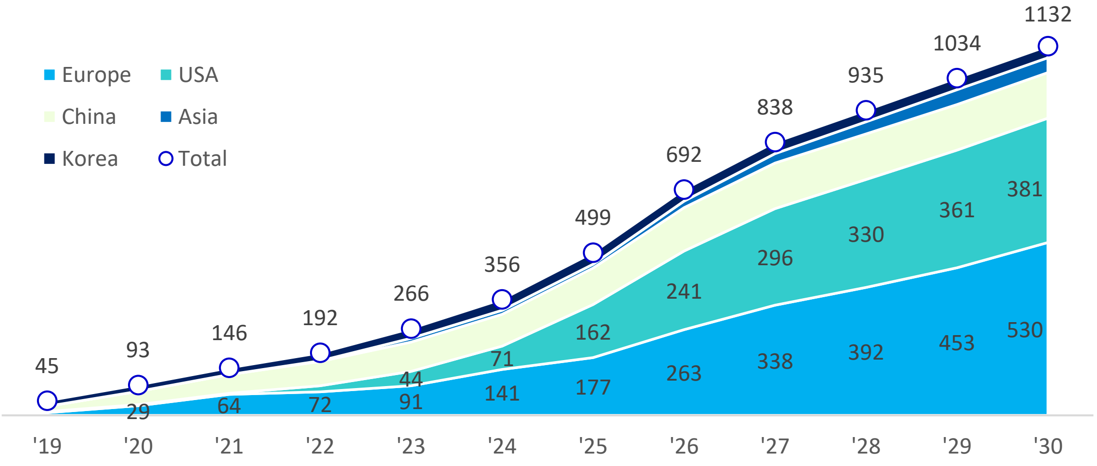


Table 3 Proportion of three Korean battery makers by production region

Region	'20	'25	'30
Europe	32%	41%	49%
USA	4%	33%	36%
China	44%	19%	10%
Asia	0%	2%	3%
Korea	21%	5%	2%

Battery types used for electric vehicles are classified into cylindrical, prismatic and pouch types. As of 2020, the global share of battery types is 36% for prismatic batteries, 35% for pouches, and 29% for cylindrical batteries, which are used almost equally.

Factors to consider when deciding on a battery type include price, design freedom, and stability. Cylindrical type is slightly more advantageous in price, but the pouch type has more room for cost reduction through design flexibility technology development compared to cylindrical type. When it comes to making predictions on usage by battery type in 2030, prismatic and pouch types are expected to dominate the market with 47% and 42% of market shares respectively. This is because there are not many major automakers other than Tesla that prefer cylindrical models. Tesla is also using prismatic battery for the Model 3 in China, receiving them from CATL. Recently, it adopted 4680, which is an improved version of the existing cylindrical shape (2170) and declared that it would be applied in earnest. It is known that it produces from its own production lines and, at the same time, receives some of the necessary demand from outside. The 4680-battery type increased the cylindrical diameter from 21 to 46 mm from the existing 2170, and increased the height from 70 to 80 mm. It is a type of battery that can lower the price by increasing energy capacity by 5 times and reducing shared subsidiary materials. In addition to Tesla, battery companies developing 4680 cylindrical batteries are Panasonic, LGES, SDI, CATL, BAK, and EVE. After 2025, cylindrical batteries are expected to be 4680-type.

2.2 Roadmap for Battery Technology

The technology development roadmap of the three Korean battery companies is divided into two major axes: improving the energy density or developing low-cost battery. Energy density improvement can be achieved by using more nickel than existing NCM 622 or NCM 721. For instance, technology is developed to come up with NCM 811 or NCM 91/21/2. It is understood that they have plans to develop and release LFP and Mn Rich (Co free) to the market, with an aim to targeting low-cost markets. When it comes to anode materials dominated by artificial/natural graphite, by adding 10 to 20 wt% of silicon to graphite, companies are trying to improve the energy density and the rapid charging characteristics at the same time. Silicon being developed for use in anode materials are commonly complex compounds of SiOx and Si-C to address the volumetric swelling issue during charging/discharging. Recently, research is being conducted in various ways so that 100% silicon can be used. All three companies aim to increasing energy density to over 320 Wh/kg around 2025. According to interviews with them, they seem to have a goal of converting from the existing liquid LiB to all-solid-state after 2026.

Table 4 Roadmap for Technology Developments

Technology		‘23	‘24	‘25	‘26
LGES	Cell E/D	300Wh/kg		320Wh/kg	
	Cathode	NCMA(Ni 86%)		NCMA(Ni > 90%)	
	Anode	Gr+SiO 5.5%		Gr+SiO 〈8%,SWCNT / Pure Si	
	Sepa, Electrolyte	SRS,New Salt(LiFSI…) Electrolyte			
SDI	Cell E/D	275Wh/kg		290Wh/kg	
	Cathode	Gen6 NCA(Ni 91%)		Gen7 NCA (Ni > 91%)	
	Anode	Gr+SCN(Si 8%)		Gr+SCN(Si 10%)	
	Sepa, Electrolyte	High-heat Resistance thin Sepa,New Salt			
SK on	Cell E/D	285Wh/kg		320Wh/kg	
	Cathode	NCM 9½ ½(Ni 88%)			
	Anode	Gr		Gr+SiO	

	Sepa, Electrolyte	High-heat Resistance thin Sepa, New Salt

2.3 Issues and Responses in Battery Industry

Major issues in the battery industry in Korea are as follows: 1) EV fire incidents and 2) supply and demand of raw materials (supply chain issues).

1) EV fire incidents

As the distribution of electric vehicles expands, the number of electric vehicle fires has also increased rapidly since 2019. Figure 5 shows the number of incidents investigated by SNE Research. Electric vehicle fires can occur for various reasons, and in most cases, the exact cause was not be able to identify as most parts of a vehicle in fire incident burnt away. From 2013 to September 2022, the number of fire incidents occurred in Tesla were 129. The rate of fire incidents was found to be the highest in North America followed by Europe, China and other regions. In terms of fire incident causes, most fires were caused by collisions, but the rate of fire incidents even during charging or being parked turned out to be high.

Figure 5 Number of EV Fire Incidents by Year

Unit: the number of incidents

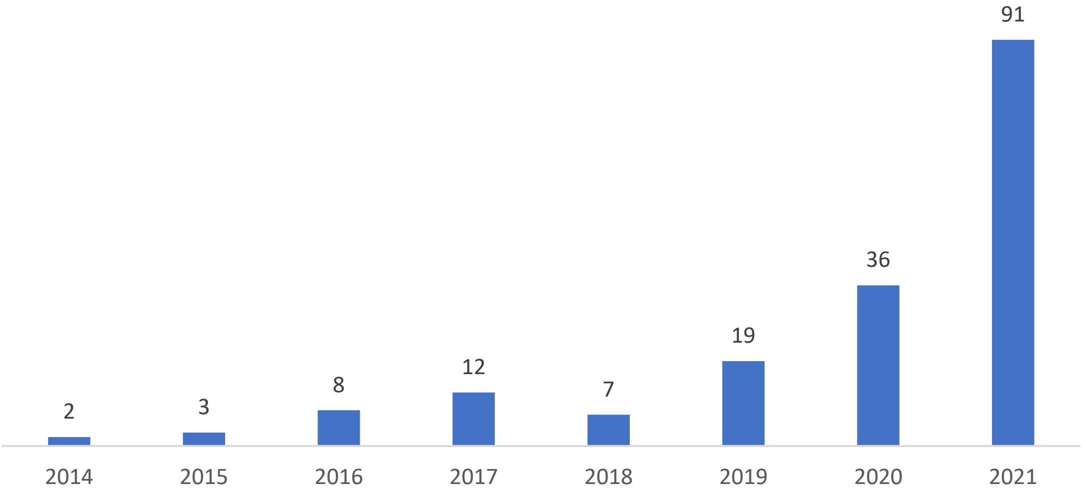
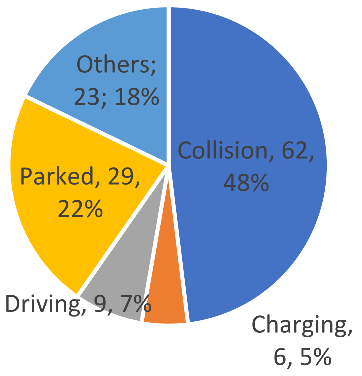


Figure 6 Rate of Fire Incident in Tesla EV ('13 ~'22)

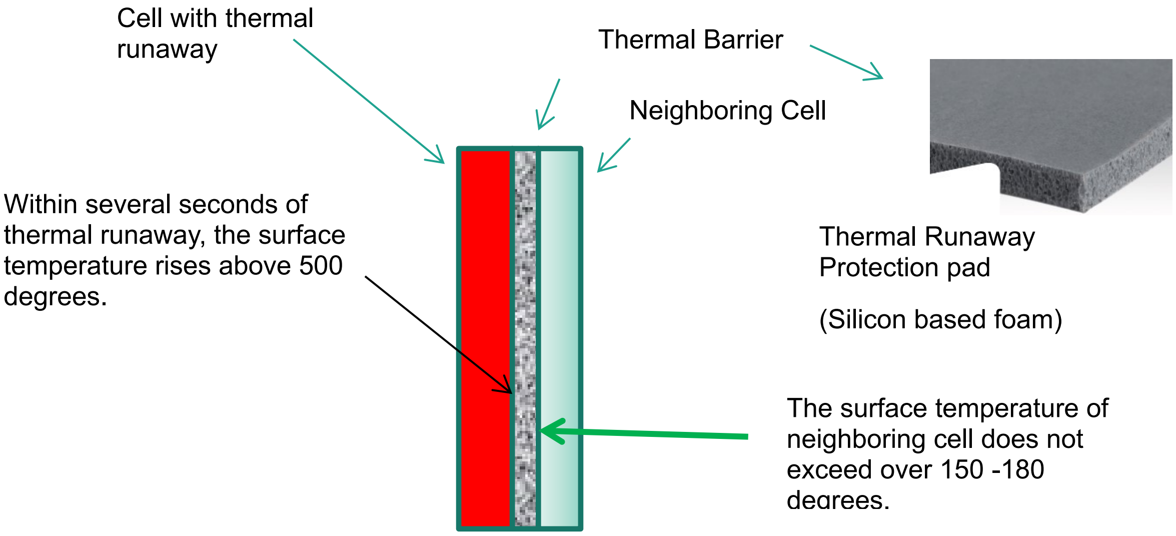
(Unit: Incidents, %)



Although various efforts have been exerted to accurately analyze the cause of electric vehicle fires and solve the problem, as long as liquid electrolyte, which is flammable, is included inside battery cell, it is very difficult to eradicate the cause of fire incidents in electric vehicles. This is the same logic that is applied to internal combustion engine vehicles which have flammable matters such as gasoline and diesel oil and thus, may catch fire in case of collision. One of the alternatives that have been considered lately was all-solid-state battery which replaces flammable, liquid electrolyte with solid material, but further technical development should be conducted before being put to practice use.

One of the major reasons for battery fire is regarded thermal runaway of battery cell. Thermal runaway usually occurs between cell and cell, module and module, and pack. Most battery makers and EV makers in the industry try to find a prevention measure against thermal runaway as a temporary solution to fire incidents in electric vehicles. To be specific, they use a special component made of materials that may prevent the propagation of fire between battery cells. During normal operation, when thermal runaway does not occur, the component works as a compressed pad between cells.

Figure 7 Schematic Diagram of Prevention Measure Against Thermal Runaway at Battery Cell



Many companies such as Mitsubishi Chemical have been working on technology development and at the same time releasing their products. They present the following features as significantly differentiating factors: electrical insulation, resistance to temperature, insulation and material that is not easily deformed by pressure.

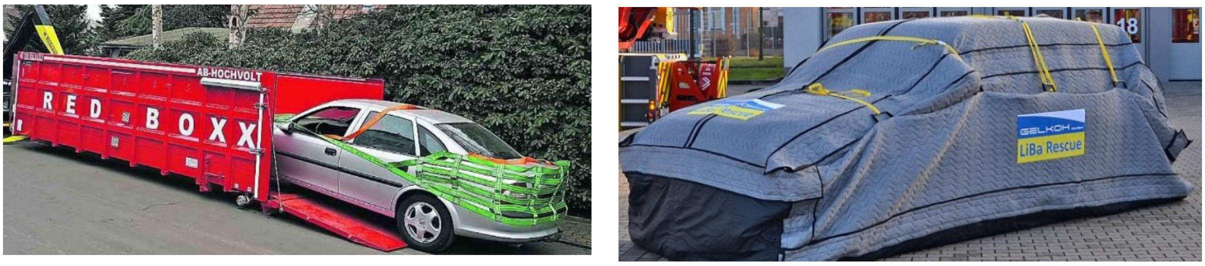
Preventing thermal runaway in battery pack is a key solution for flame retardancy. In other words, containing fire occurred inside pack and keeping it from propagating to outside of the pack is essential and vice versa. During normal operation, it works as a gasket sealing for pack, but once fire incident occurs, it transforms into char due to the heat and swells, working as fire barrier. Figure 8 below shows how it turns into char due to the heat and swells. It should block fire, smoke, and hot gas, without releasing any toxic gas. It should be a soft material with watertightness and airtightness, and at the same time, it should be resilient.

Figure 8 Example of Fire-Retardant Material for Module/Pack

If the electric vehicle battery is misused or subject to mechanical shock, heat builds up inside the battery pack/cell and can cause exothermic collapse. In this case, gas is generated and fire is triggered . This phenomenon can be caused by various reasons, but the ultimate cause was the contact made between the positive and negative electrodes inside the battery cell, leading to thermal runaway.

To prevent thermal runaway of battery cells, there have been continuous technology development at the level of cell/module/battery pack. At the same time, there have been studies to minimize damage in case of fire[2]. Those developed methods have their benefits and shortcomings, and continuous modification and improvement are expected in coming years. Figure 9 displays some of the pilot products.

Figure 9 Response Measures In Case Of EV Fire



(A) Rdeboxx by Ellermann

(B) LiBa Rescue by Gelkoh

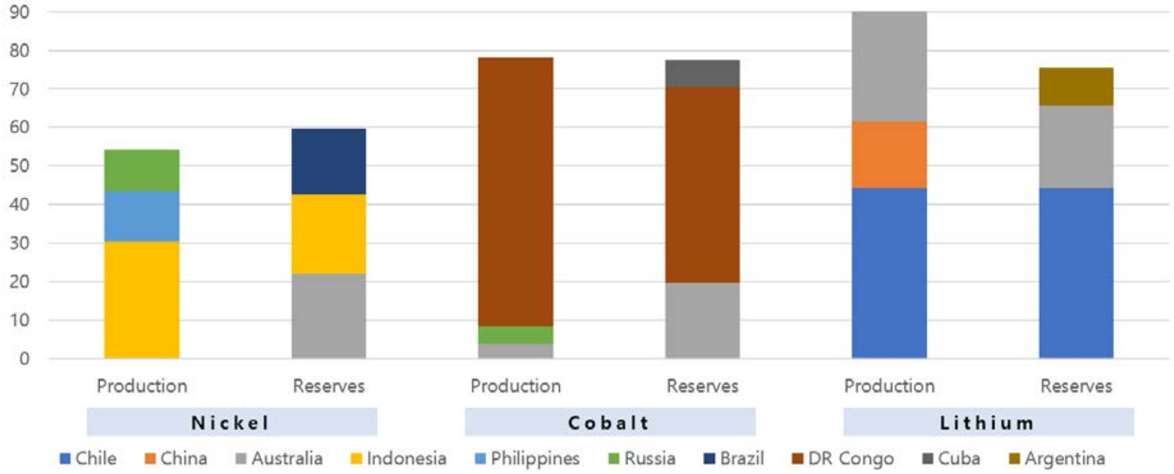
(C) Recover-E-Bag by RuGo Bags

(D) Muller Safety Trailer(MST)

(2) Issues With Raw Material Supply and Demand

Raw materials used for components and materials of lithium battery are lithium, nickel, cobalt, manganese, iron, phosphate, copper, aluminum, graphite, etc. There are also resin-based components, and titanium or silicon compounds are sometimes used. For cathode materials, Li, Ni, Co, Mn, Al, F, and P are mainly used, while for anode materials, graphite and Si are used. The positive substrate mainly uses Al, negative substrate uses Cu, and for electrolyte and separator, Li and PE are mostly used. Taking the 2021 demand for cathode materials and yield into consideration, if the consumption of key raw materials at a 30-GWh battery production facility is calculated[3], it is estimated that 19,000 ton of lithium (based on LCE), 14,000 ton of nickel, 6,000 ton of cobalt, and 4,000 ton of manganese are needed. Figure 10 shows the global top 3 countries whose production volumes and reserves of nickel, cobalt, and lithium are the highest in the world.

Figure 10 Global Metal Reserve and Production (Unit:%)



Key raw materials of lithium secondary batteries are disproportionately deposited in few countries: nickel in Indonesia, cobalt in DR Congo, and lithium in Chile. The lead time for mine development is very long – approximately 16 years, and the supply sensitivity is low in response to changes in market demand and new mine development. Minerals go through refining and smelting and are turned into cathode and anode. If we look at the share distribution of up-stream market, we may come to understand how serious the disproportion in the market has been in terms of mineral deposit in countries.

Table 5 Major Upstream Market Shares (2019)

Metal	Mine			Refinement			Anode/Cathode Materials		
	Europe	US	China	Europe	US	China	Europe	US	China
Nickel	8%	0%	31%	13%	1%	65%			
Cobalt	0%	0%	1%	17%	0%	82%			
Graphite	1%	0%	65%	0%	0%	100%			
Lithium	0%	1%	9%	0%	4%	59%			
Manganese	0%	0%	6%	7%	0%	93%			
Cathode Material							0%	0%	61%
Anode Material							0%	0%	83%

In case of graphite, a key material for anode, 65% of graphite mines, 100% of refining/smelting, and 83% of anode material manufacturing are occupied by China. In addition, China also dominates the cobalt market by occupying 82% of refining/smelting, and 61% of share in the cathode market, meaning that the global dependence on China is very high in terms of key raw materials and intermediate goods. After the Covid-19 pandemic, the price of key metals used for secondary battery production has soared due to increasing demand and logistical disturbance. Compared to the early 2021, the prices as of the end of 2021 are as follows: lithium increased by 431%, nickel by 17%, cobalt by 113%, and manganese by 24%. The IRA recently enacted in the US mandates that a certain level of critical minerals (lithium, nickel, cobalt, etc.) used to produce EV batteries must consist of those made in the US or in countries that have entered FTAs with the US. Specified percentages of the vehicle battery's critical minerals should originate from a US free trade agreement ("FTA") partner or be recycled in North America. The US tax credit of $7,500 will be applied to purchases of new electric vehicles. For the K-trio, it is an imminent issue to reduce their dependence on key minerals held by China and refining/smelting process in China. However, it seems that they need some time to build new lines and secure necessary technologies.

3. Battery Supply Chain

The working principle of lithium secondary battery is the charge and discharge in which lithium ions transfer between cathode and anode. The intercalation and deintercalation of ions in electrodes should be facilitated, and the structure of electrodes should remain stable during charging and discharging, while the electrolyte should facilitate the transfer of ions.

Table 6 Major Components of Lithium Ion Battery

Category	Major Components
Positive/Cathode Electrode	Active material, conductive material, binder, substrate (Al)
Negative/Anode Electrode	Active material, conductive material (if necessary), binder, substrate (Cu)
Separator	Microporous PE or PP film
Electrolyte	Lithium salt + organic solvent (carbonate-based material)
Safety devices	Safety Vent, PTC, protection circuit

Lithium secondary battery that is currently commercialized – that is lithium-ion battery – is composed of cathode, anode, separator, organic solvent electrolyte, and other safety devices. Both positive and negative electrodes consist of materials that make electrodes active, conductive material, binder, and current collector. Usually, transition metal oxide is used for active cathode material. One of the most popular active materials for cathode is LiCoO2. Cathode active material itself is low in electrical conductivity. As a supplement, carbon-based materials are used as conductive additives. Binders are also added to keep cathode active materials and conductive additives stick to aluminum current collector.

Graphite is used as the most popular active material for anode. Same as the cathode, binders are added to keep anode active materials stick to copper current collector. In general, as graphite anode active materials have sufficiently high electrical conductivity, no conductive material is added, but it depends on circumstances.

The separator is used to prevent electrical contact between the anode and cathode. Polymer film such as polyethylene (PE) or polypropylene (PP) is often used.

Organic electrolyte is a medium for moving lithium ions. Lithium salt and carbonate-based organic solvent are used. In general, when a liquid electrolyte is used, such battery is referred to as a lithium-ion battery (LiB), while when a polymer electrolyte is used, it is called a lithium-ion polymer battery (LIPB).

In the case of lithium secondary batteries, as unstable lithium is used, there is an inherent risk of explosion, and to prevent this, safety devices such as safety vents are included.

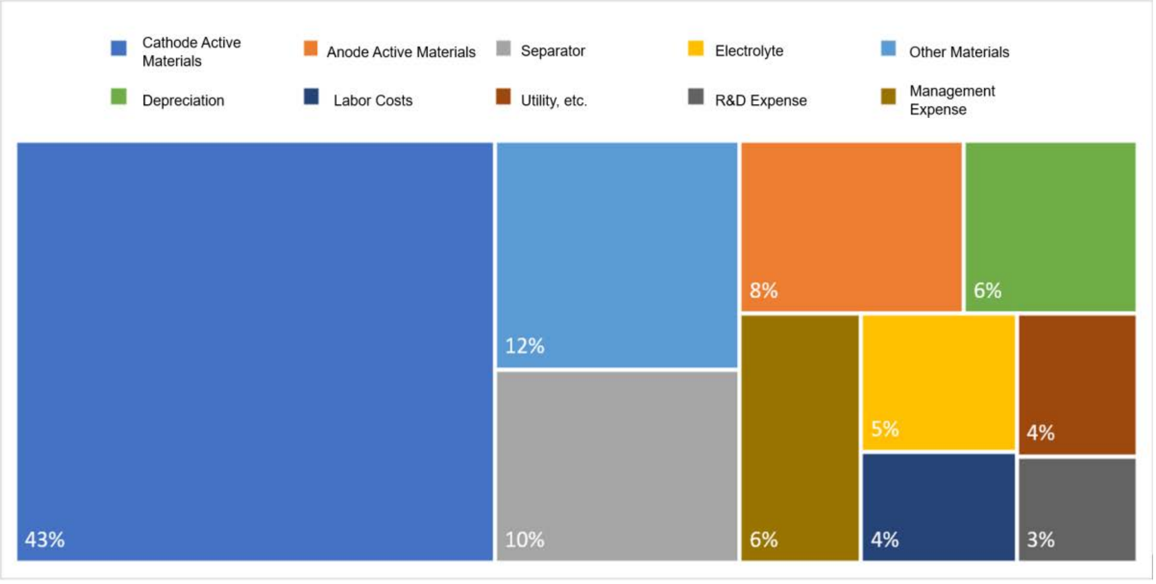
Lithium secondary battery commercially traded in the market can be categorized into different types according to their shapes and component materials. By battery shape, battery can be categorized into three different types: cylindrical type mostly used for laptops; prismatic type using metal cans as exterior materials; pouch type using compound exterior materials made of aluminum and plastic; and round-shape coin battery.

Cylindrical battery has the advantage of being mass-produced through a standardized manufacturing process, while prismatic battery has the advantage that it is possible to manufacture large cells and has excellent safety due to its hard exterior. In case of a pouch-type battery, it has the advantage of being free in molding and being able to sell at a low price because there are few parts. Coin batteries are generally used in small wireless devices such as wireless earphones.

As mentioned above, a lithium secondary battery is composed of four major materials: positive electrode active material, negative electrode active material, separator, and electrolyte. In addition, it consists of conductive materials, binders, and substrates (Al and Cu) constituting electrodes, battery cases or packaging materials, tabs for electrical connection, and safety devices (Vent, PTC, protection circuit, etc.) to ensure battery safety.

Based on the cost data in 2021, cathode active materials accounted for 43% of the entire battery production cost, while the 4 major components accounted for 65% of the entire cost[4].

Figure 11 Composition of Cell Price (2021)



In the case of cathode active materials, lithium is a part of the crystal structure and moves out of the structure in the form of ions during deintercalation, requiring structurally stable, transition metal-based oxide materials to be mainly used. For anode active materials, to stably store lithium ion moving out of the positive electrode and provide sufficient electromotive force, materials whose standard reduction potential is not significantly different from lithium are used. For electrolyte, lithium salt and organic solvent are used as they maintain electrochemical stability within the operating voltage range and have high thermal and chemical stability. In addition, as a separator to prevent short circuit due to electrical contact between the positive and negative electrodes, polymeric or ceramic materials that can melt at high temperature are used.

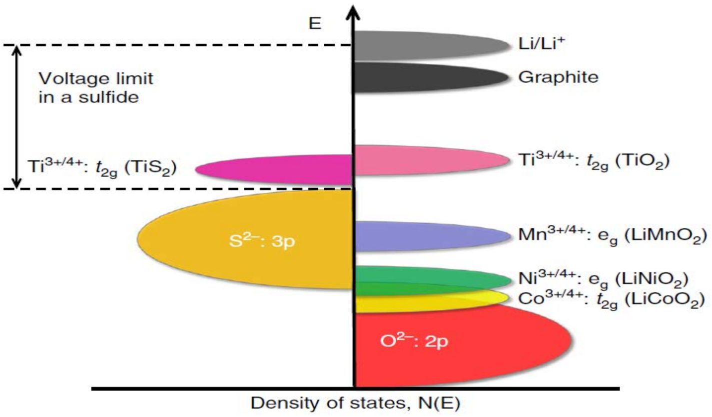
3.1 Cathode Active Material

Among the components of a lithium secondary battery, the cathode active material accounts for 43% of the total cost of a lithium secondary battery. It is the most important material that determines the basic performance of lithium secondary batteries, such as capacity and safety. As the cation of the cathode active material, 3d transition metal is mainly used. Compared to 4d and 5d transition metals, 3d transition metal has higher electrode potential, and is relatively light and small in size. 3d transition metal is advantageous in capacity per unit weight and unit volume. In terms of structural stability, given repeated oxidation and reduction reactions, chalcogens are superior to halogens to be used for anion. Among chalcogens, oxygen is the most efficient.

For the conversion neutrality of transition metal oxides during charging and discharging, when cation is intercalated and deintercalated between the positive electrode and anode active material or moves inside electrolyte, it should be done with ease and speed. If fast charging and discharging are desired with cations having a reversibly broad range of redox potential inside the structure or minimal changes in the crystal structure of electrode active materials are sought after, cations in smaller size and lower charge number, whose coherence with active material is weaker, should be chosen. Lithium ion is suitable for cation as it is smaller in size and has lower charge number compared to other candidate atoms. Given the battery potential, the standard reduction potential of lithium is -3.040 V, so it is more advantageous to increase the voltage of battery.

The first cathode active material developed for lithium-ion battery is TiS2. Professor Whittingham, working as a researcher at Exxon, found out that lithium ions can be stored in layered structure and then developed lithium secondary battery with TiS2 as cathode and lithium metal as anode[5]. However, TiS has a shortcoming that its operating voltage is below 2.5V and lithium metal should be used as anode, which may trigger a safety issue.

Figure 12 Energy Band



Later, Professor Goodenough conducted research on the application of oxide-based cathode active material instead of sulfide. As seen Figure 12, the energy band of O2- is located lower compared to that of S2-, enabling to use the transition metal like Co having an energy band lower than lithium and thus enhancing the cell voltage up to nearly 4V. Furthermore, the oxide-based cathode active material contains lithium, allowing to use the graphite-based anode active material without lithium and thus dramatically improving the stability of secondary battery.

Cathode active materials are LiMO2, lithium transition metal oxide in layered structure; LiM2O4 in the spinel structure; and LiMPO4, lithium transition metal polyacid compound in the Olivine structure. In their molecular formula, M stands for transition metal.

There also have been active research on simply mixing cathode active material with different crystal structure and composition depending on intended use, coating the surface, or forming compounded matters. For instance, if the high-capacity, cathode active material with low electric conductivity but stable structure is applied with surface treatment with the cathode active material that is small in capacity, high in price, but high in electric conductivity, then we can have cathode, active material with high capacity and high power. Table 7 shows the discharging capacity and features of various active materials used in lithium secondary battery.[6]

Table 7 Different Types of Cathode Active Materials for LIB and their Features

Chemistry	Lithium Cobalt Oxide	Lithium Manganese Oxide	Lithium Nickel Manganese	Lithium Iron Phosphate	Lithium Nickel Cobalt Aluminum Oxide
Short Form	Li-cobalt	Li-manganese	NCM	Li-phosphate	Li-aluminum
Abbreviation	LiCoO2 (LCO)	LiM2O4 (LMO)	LiNiMnCoO2 (NCM)	LiFePo4 (LFP)	LiNiCoAlO2 (NCA)
Nominal Voltage(V)	3.6	3.7	3.6	3.2	3.6
Specific Energy (Wh/kg)	150-200	100-150	150-220	90-120	200-260
Cycle Life (ideal)	500-1000	300-700	1000-2000	1000-2000	500
History (year)	1991(Sony)	1996	2008	1996	1999
Comments	High energy limited power, Market situation has stabilized	High power, less capacity, safer than Li-cobalt, often mixed with NCM to improve performance	High capacity and high power. Market share is increasing	Flat discharge voltage, high power low capacity, very safe, elevated self-discharge	Highest capacity with moderate power. Similar with Li-cobalt

To be used as cathode active materials for LIB, materials should have characteristics as follows:

- For intercalation and deintercalation of a large amount of lithium ion and increased energy efficiency during charging and discharging, materials should have a reversible reaction in a broad range of composition and constant plateau.
- To have high capacity per unit weight or unit volume, materials should have a dense structure, and to have high power, their electric conductivity and ionic conductivity should be high.
- Cycle efficiency should be high. Efficiency gets lower if negative reactions unrelated to the circulation of lithium ion at cathode and anode occur.
- Irreversible phase transition in the crystal structure may shorten the battery life. It should be made sure that such phase transition during charging and discharging will not occur. In addition, if the volumetric

change of crystal lattice is large, active materials may detach from the current collector and thus, decrease the capacity.

- Materials should be chemically or electrochemically stable not to react to electrolyte and should be thermally stable, too.

- Particles should be spherical, and the distribution range of particle size should be wide. This is to enhance the electric conductivity along with the contact efficiency between particles, not to damage the thin aluminum film – which is the current collector – when making the pole plate, and to get relatively high energy density per volume by increasing the filling rate at the pole plate.

- The elements should be at an affordable price and environmentally friendly.

The most representative layered structure type cathode active material is LCO which has been widely used from the early phase of commercialization as its capacity and life characteristics are fine. However, to reduce the production cost and strengthen the stability, more and more companies choose NCM instead of LCO. NCM and NCA, also layered structure type cathode active materials, partially replace expensive and toxic cobalt with nickel, manganese, or aluminum, leading to the reduction in cost and improvement in battery characteristics. In addition, by increasing the content of nickel, they can achieve relatively high capacity at the same ceiling voltage, allowing them to be used more often. Currently, NCM and NCA have been already adopted as cathode active materials for lithium secondary battery for various IT applications and EVs. Research on cathode active materials is heading towards the growth of nickel content to increase the energy density and lower the content of cobalt.

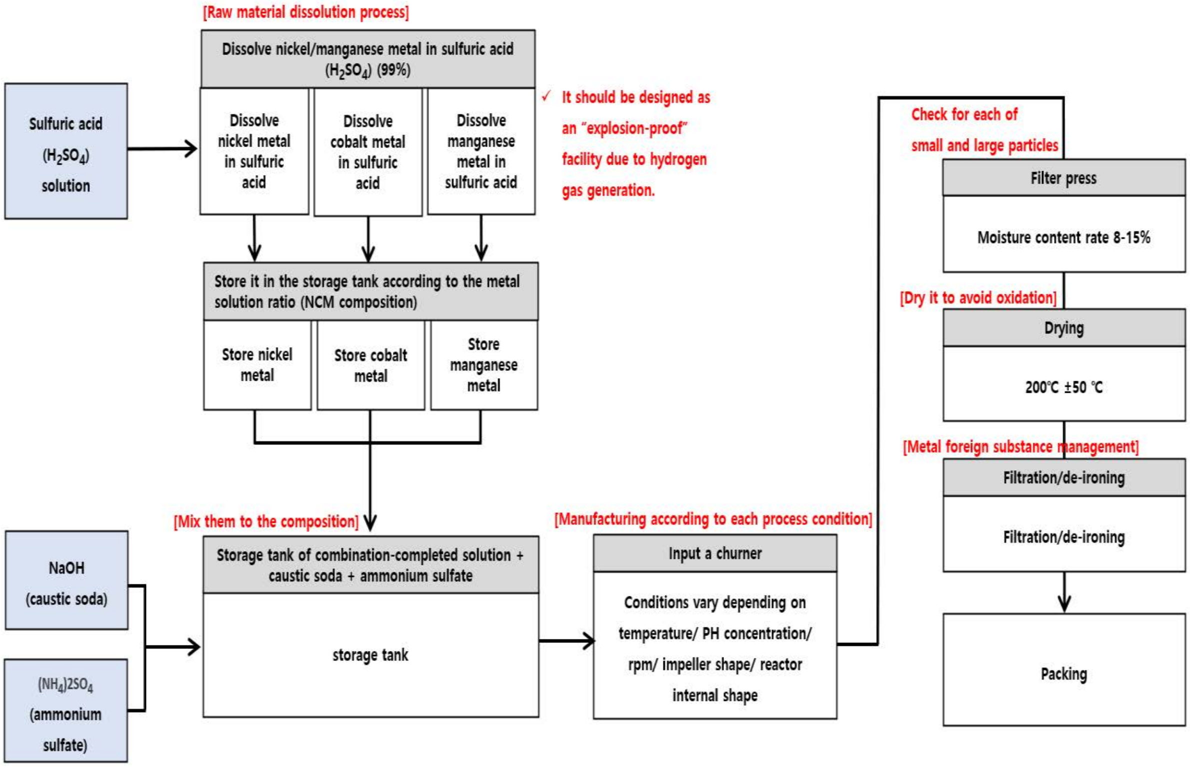
Spinel-structured cathode active material, LMO is eco-friendly and low-cost manganese-based material whose price competitiveness is superior to other cathode active materials in the market. Thanks to its price competitiveness, it has been adopted as cathode active material for lithium secondary battery for electric vehicles, but if the operating temperature rises above 60 ℃, manganese dissolves in the electrolyte, which is pointed out as a shortcoming in structural instability. In addition, due to its low theoretical capacity, less and less battery makers have chosen to use it.

Olivine structure type cathode active material, LFP has superior safety compared to other cathode active materials, thanks to strong bond between phosphorus and oxygen (P-O bond). It can be also obtained from using eco-friendly raw materials whose cost is also affordable. With its price competitiveness, LFP has drawn a host of attention from the industry as a cathode active material for lithium secondary battery for EVs. However, compared to Spinel-structured cathode active material, LFP has lower theoretical capacity, low electric conductivity, and ionic conductivity. LFP also has more complexity in process control compared to other materials. Patent issues related to LFP also are a huge obstacle for battery makers who want to make lithium-ion batteries using LFP. Recently, as a longer driving range of electric vehicles has been regarded as an important factor in choosing vehicle models, the application of cathode active materials which do not only have the stability and safety but also high capacity has been seriously considered. In case of Tesla from the US, they adopted NCA whose safety is relatively poor but other battery characteristics are superior with high capacity and started to produce their electric vehicles. In case of NCM, the market has seen increases in the content of Ni in composition to obtain high capacity. LFP whose stability is the most superb among others has been mainly adopted by the Chinese makers as cathode active material for lithium secondary batteries for electric vehicles due to several shortcomings of LFP: low voltage, poor power output, shorter battery life, and lower energy density.

Precursor is a metal compound used as a major material for cathode of secondary battery. Precursor production is largely divided into a liquid phase method and a solid phase method. In the case of the Ni-based liquid phase method, the processes of metal solution preparation → co-precipitation → washing and drying are performed. First, a metal solution is prepared by dissolving the metal in a strong acid solution, like sulfuric acid. Since metal ions in solution are weakly bound to electrons of water molecules (oxygen), a complexing agent is added to facilitate the precipitation, where Ammonia (NH_3) is mainly utilized. The reason is that nitrogen in ammonia provides electrons to be weakly bound with metal ions. The complex ion thus formed in this way lies in the state where it can stably react with other anions, and at this point, when a solution, such as NaOH and others, is added, hydroxides are formed with OH^- ions. When this hydroxide coheres, it is precipitated, and after this precipitation is washed, it can be used as a precursor. In the case of the solid phase method, a precursor can be obtained through a pulverization process after physically mixing metal and metal and then heat-treating it. In the case of chemical and physical bonding, there are advantages and disadvantages. According to the characteristics of the cathode active material, precursors can be manufactured in various forms having different manufacturing method, composition, particle size, shape, impurities, etc.

The production process of NCM precursor is described in Figure 13 below. The production process can be divided into raw material dissolving process, composition control, process control, selection of small and large particles, drying and metal foreign substance management.

Figure 13 Precursor Process Flow (NCM)[7]



The material types used as precursor raw materials can be largely classified into three. Metal sulfate salts, metal nitrate salts, and metal hydrochloric acid salts can be used, but metal sulfate salts, advantageous in terms of price and process, are mostly used. The metal sulfate salts used to manufacture NCM precursors include nickel sulfate salt, cobalt sulfate salt, and manganese sulfate salt; these metal sulfate salts are prepared and utilized as follows according to the manufacturing and raw material purchasing methods.

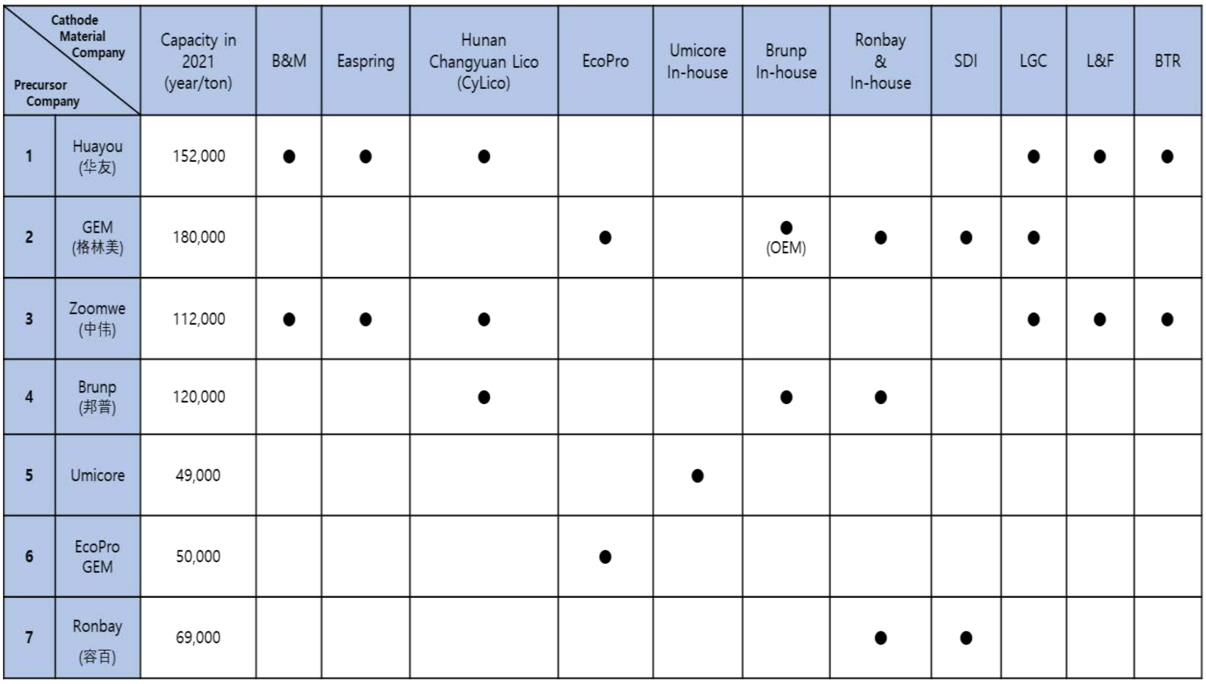
(1) Used by dissolving metal sulfate salt in water

Dissolving nickel sulfate salt, cobalt sulfate salt, and manganese sulfate salt in water to prepare an aqueous solution of each metal sulfate salt, it is mixed in a predetermined ratio to prepare an aqueous composite metal salt solution, which is used as a raw material for manufacturing a precursor.

(2) Used by dissolving metal in sulfuric acid solution

Metal sulfate salt was prepared by dissolving nickel, cobalt, and manganese metals in sulfuric acid solution and then diluted with water to prepare an aqueous solution of each metal sulfate salt; after mixing it in a predetermined ratio, an aqueous complex metal salt solution is prepared and used as a raw material for manufacturing a precursor. However, since hydrogen gas is generated when metal is dissolved, the melting device must be designed to be explosion-proof.

Table 8 Precursor Supply Chain (As of 2021)



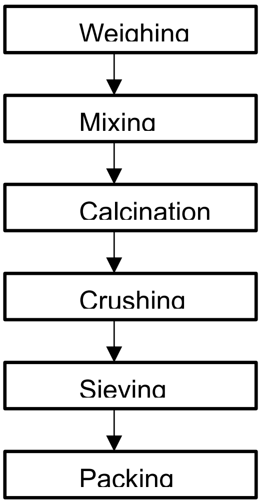
Cathode Material Company Precursor Company		Capacity in 2021 (year/ton)	B&M	Easpring	Hunan Changyuan Lico (CyLico)	EcoPro	Umicore In-house	Brunp In-house	Ronbay & In-house	SDI	LGC	L&F	BTR
1	Huayou (华友)	152,000	●	●	●						●	●	●
2	GEM (格林美)	180,000				●		● (OEM)	●	●	●		
3	Zoomwe (中伟)	112,000	●	●	●						●	●	●
4	Brunp (邦普)	120,000			●			●	●				
5	Umicore	49,000					●						
6	EcoPro GEM	50,000				●							
7	Ronbay (容百)	69,000							●	●			

(CAM is the abbreviation for Cathode Active Material, while P-CAM stands for Precursor Cathode Active Material.)

As shown in Table 8, most of precursors are produced by companies situated in China, which makes it important to focus on supply chain issues and required countermeasures in future.

The cathode material manufacturing process follows a typical ceramic process. That is, each raw material is weighed and uniformly mixed, and then calcined according to the chemical components of the material that is to be finally manufactured. After pulverizing the calcined material, it is sieved and packaged to complete the product of the cathode material. The major manufacturing process is shown in Figure 14[8].

Figure 14 Manufacturing Process of Cathode Material for Lithium Secondary Battery



Each raw material is weighed according to the recipe.

All the raw materials ate mixed as much uniformly as possible.

Reaction by heat (Removal of Carbonate, Hydroxide, etc.)

Crush the condensed reactant to the desired particle size.

Filter out the unbroken aggregates.

(1) Mixing

Each weighed raw material is transferred into the mixer. In general, Henschel mixer is used, and revolution of agitator, revolution of chopper, exhaust temperature, mixing time, etc. are the main control variables. Materials used are P-CAM, Li-OH/LiCO2 compounds, doping agent and coating agent.

(2) Calcination

The raw materials mixed uniformly in the previous process are filled in the setter and pass through the calcination furnace. A continuous type is used as a calcination furnace.

The major control variables in the calcination process are charge amount of each setter, calcination temperature, increase rate of temperature, atmosphere control by oxygen concentration and flow rate control, and total calcination time. Most of calcination furnaces that are currently being used are fully automated. The calcination temperature varies depending on the cathode material, but is usually around 1000°C, and the total calcination time is around 24 hours.

(3) Crushing

The calcinated cathode material is crushed to have a certain size. This process normally has primary crush and secondary crush. In the primary crush, the material is crushed finely under mm by using a roll crusher, etc. Since the fired body is calcined instead of being sintered, it can be pulverized without too much difficulty, and this is sometimes called disintegration. The secondary crush mainly uses Air Crushing Mill, etc., and the main control factors are crushing revolution number, sieving revolution number, and supply speed. The fine powder out of the crushed particles moves on by the air pressure charged into the grinder, and the less-crushed particles can be more finely crushed continuously by being crushed again.

(4) Sieving

Crushed particles are filtered through a sieve to filter out possible aggregates or granules, and an ultrasonic sieve is usually used. The final sieved product is sealed and packed in aluminum bags, etc.

(5) Magnetic Separation

Every cathode material manufacturer has self-sorting process using electromagnet in between processes where the manufacturer considers appropriate. And de-ironing is usually performed during transfer process. Fe impurity content that cathode materials require is very small under ppm. De-ironing process makes it possible to prevent accidental Fe input, such as input of foreign materials caused by wear and tear, etc., which may occur during manufacturing process. Particularly, such iron impurities greatly affect safety of lithium secondary batteries, so efforts should be made to maintain the concentration at ppb level.

Table 9 K-trio Battery Makers' Cathode Material Supply Chain (2019)

Korea Battery Makers	Supplier	Purchasing Portion (%)	Material Type
LGES	LGC	33	NCM622, NCM712, NCM811, NCMA
	Nichia	27	NCM622, NCM811, NCMA
	B&M	20	NCM811
	Umicore	11	NCM811
	POSCO	9	NCM622, NCM811, NCMA
SDI	Umicore	35	NCM622, NCM811
	Ecopro BM	22	NCA
	L&F	15	NCM622, NCM811, $NCM9^{1/21/2}$
	SDI	20	NCM111, NCM622, NCA
	Mitsui	5	LMO
	Basf-Toda	3	NCA
SK-On	Ecopro BM	55	NCM811
	Easpring	13	NCM622, NCM811
	L&F	24	NCM523, NCM622, NCM811, $NCM9^{1/21/2}$
	Reshine	8	NCM523, NCM622

(Ni-Rich NCM) Challenges[9] and Countermeasures

Typical cathode materials have available capacity of 150 to 170 mAh/g level. Improving the available capacity of the cathode material is essential to achieve a driving range required by electric vehicles after one-time charging. So, many research and developments have been carried out regarding Ni-rich cathode materials to realize capacity of 200 mAh/g or more by increasing the content of Ni in NCM523 to more than 80% of the total transition metal.

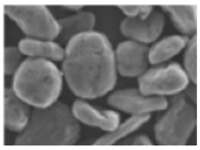
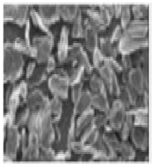
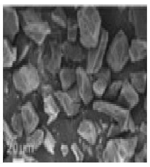
Ni-rich NCM-based cathode materials are more likely to have problems as the content of Ni increases. Inside the material, problems occur such as cation mixing in the synthesis process and charging/discharging process, formation of rock salt structure NiO secondary phase, phase change that occur during charging/discharging, which results in degradation of the mechanical properties. Meanwhile, on the surface, problems occur such as degradation of the material due to interface instability in high temperature and high voltage environment and safety degradation due to the surface residual lithium compound when the material is applied to a battery.

Therefore, technology that can solve these problems of the Ni-rich NCM-type cathode material should be developed to ensure stability and reliability of the material. Recently, various studies have been actively conducted to improve its structural instability; (1) improving electrochemical properties by doping materials such as Al, Ti, Cr, Mg, Ga, or Fe, (2) removing LiOH and Li_2CO_3 that remain on the surface by cleaning cathode active materials to improve stability in batteries, stability of electrolyte and stability at electrode interface, or (3) coating a surface by using dry or wet method.

3.2 Anode Active Materials[10]

The percentage of lithium secondary battery production cost that anode active materials has is approximately 8%, relatively lower than that of the other key materials, but efforts to reduce the production cost of anode materials have been continued. In order to improve the performance of lithium secondary battery, the energy density of anode active materials should be enhanced. To do so, we can take one of the following four methods: (1) change of electrode material, (2) improvement in the application technology, (3) improvement of electrode packing technology, and (4) enhancement of charging/discharging efficiency of anode. However, methods (2), (3), and (4) are related to the optimization and design of internal spaces of battery, which seem to have already reached an upper limit for improvement. In this regard, the energy density of anode can only be improved by changing electrode materials. To replace the carbon-based materials that have been previously used, metal-based materials such as Si and Sn are considered as potential candidates, but still there are limitations in their use due to reduction in battery life caused by volumetric swelling during charging and discharging. In this regard, so far, graphite-based, and carbon-based anode active materials have been adopted as a key material for anode in lithium secondary battery. Carbon-based materials used for anode in lithium secondary battery can be categorized into graphite-based (high-crystalline carbon) and carbon-based (low-crystalline carbon).

Table 10 Major Characteristics of Anode Active Materials

Materials	Artificial Graphite	Natural Graphite		Disordered Carbon **(Soft/Hard Carbon)**	Silicon **(SiO, Si-C, Si-Alloy)**
		High-end	General		
Morphology					
Capacity (mAh/g)	280~360mAh/g	360~370mAh/g		235~315mAh/g	400~1200mAh/g
Capacity Retention @300 cycle	93%	85~88%	81~83%	98%	TBA
Coulombic Efficiency	95%	95%	93%	80~87%	80~90%
Company	• Hitachi • Mitsubishi • Nippon Carbon	• BTR • Hitachi • Mitsubishi • Nippon Carbon	• BTR • Shanghai Shanshan	• Hitachi • Nippon Carbon • Kureha	• Shin-etsu • BTR • Shanghai Shanshan

Graphite-based anode active materials often refer to artificial graphite and natural graphite, while carbon-based anode active materials refer to soft carbon and hard carbon. Graphite-based anode active materials, of which the crystallinity degree is high after heat treatment at high temperature, have high density and thus can be used as anode active materials for high-capacity battery. Carbon-based anode active materials, of which the crystallinity degree is low, are often used as anode active materials for high-power battery. Characteristics of each material are as follows:

- Artificial Graphite: Coke (a coal-based, solid fuel made by heating coal or oil in the absence of air) power is mixed with a bonding agent and then gone through firing. After a complete carbonization, the mixture is heated at 2,500 ~3,000 ℃ inside the electric furnace. Artificial graphite has a high degree of crystallinity, a more stable structure and 2~3 times longer battery life compared to natural graphite.

- Natural Graphite: At the nascent stage of commercialization of lithium secondary battery, natural graphite, whose initial charging efficiency is low, was not preferred to artificial graphite in most cases. However, thanks to surface treatment, the initial charging efficiency of natural graphite has been increased to 90% of that of artificial graphite. Since then, the use of natural graphite of which cost is more affordable, has been gradually expanded.

- Soft Carbon: Small graphite crystals are orderly aligned and thus can be easily graphitized by heat treatment at 1,800~2,000 ℃. It is also regarded mechanically soft.

- Hard Carbon: With small graphite crystals clustered disorderly, hard carbon is difficult to be further graphitized or turned into a layered structure. With its superior charging/discharging rate of lithium ion, hard carbon is widely used as anode active material for high-power lithium secondary battery.

Graphite-based anode materials have already had the capacity that is nearly close to theoretical capacity, and if the density of electrode is increased, the battery life and charging characteristics aggravate. In other words, graphite-based materials have already faced a limit in enhancing the energy density without modifying the materials in a more effective and efficient way. In this regard, Si-based anode materials have been actively studied as an alternative to enhance the energy density of cell as Si-based anode materials have theoretical capacity almost 10 times greater than that of graphite-based materials. Si-based anode materials have their biggest issue of volumetric swelling. There have been lots of research and development going on to find out ways to embody a variety of shapes and structures that can minimize or suppress volumetric swelling.

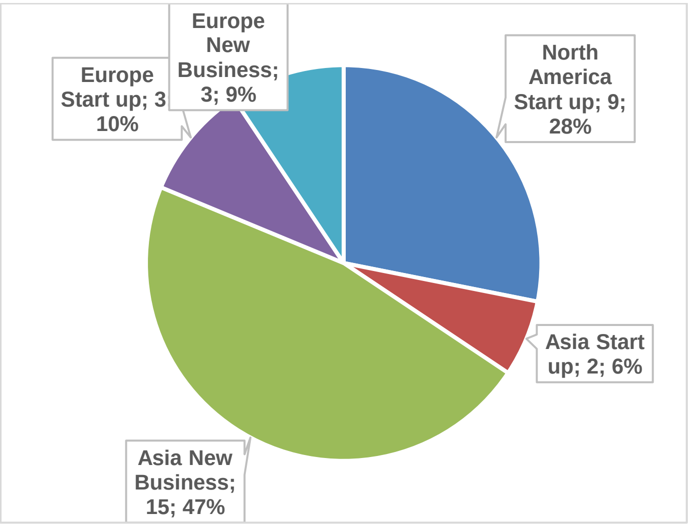
One of the basic approaches is to make Si particles in nano particles. In general, nano Si-based anode materials have several advantages as follows:

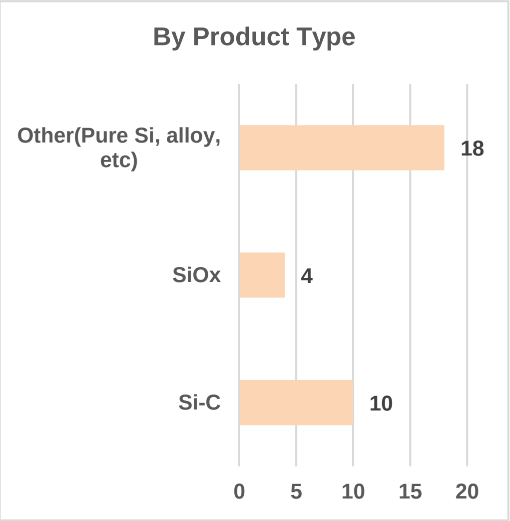
First, reactions in larger-than-micro particles that cannot take place theoretically can be realized in room temperature. Second, with reduced diffusion distance of lithium ions, the realization of maximum capacity and reaction rate – in other words, the power characteristics of battery – can be enhanced. Third, Li-Si alloy alleviates the level of displacement and stress occurred during phase change, alleviating the mechanical damage of Li-Si alloy particles. Generally, the destruction of brittle materials such as Li-Si alloy occurs due to the dislocation spread from a crack tip and the related crack formation. If the size of crystal grain of this material is below 20 nm, potential is transmitted to the surface at a rapid pace, known to be causing almost no mechanical damage across the entire grain. Theoretically, the formation and transmission of crack appear when the size of grain is larger than a certain critical size. In many cases, such critical size is often larger than that of nano-sized grain, meaning that making nano particles and crystal grains can become the most significant technical issue to suppress the mechanical deterioration. In addition, it causes mechanical destruction in Li-Si alloy materials. However, in the structure of nano-sized crystal, the diffusion concentration gradient may lapse at a rapid pace, alleviating the destruction of material due to differences in concentration gradients.

However, nano Si particles do not always have advantages only. Their shortcomings are as follows: First, the density of electrode may reduce, which may, in turn, lower the energy density per volume. Second, the surface area, increased thanks to nano particles, may increase the side reaction and other thermal reaction of liquid electrolyte, possibly causing problems with battery safety and reversible efficiency. Third, with smaller particles, it becomes more difficult to materialize a constant and uniform electrode at the slurry and electrode production processes. Fourth, producing active materials using the nano technology may lead to a possible increase in the production cost.

Currently, many battery makers have been reviewing the application of Si-based anode materials to overcome the capacity limit of existing graphite anode material. However, as mentioned above, issues caused by swelling have not been completely tackled, making it difficult to entirely replace the existing graphite anode. We have conducted research on 32 companies who mass produce or develop silicone anode materials. Figure 15 shows those companies grouped by different regions.

Figure 15 Silicone Anode Material Manufacturers by Region/ Company Type / Product Type





In Asia, there are 17 companies (53%), and most of them developed a new business unit by adding silicon anode material to their business portfolio. On the other hand, in Europe and the US, most of companies are start-ups who opened their business based on the utilization of silicone technology. There is a growing number of companies to develop and produce a variety of product types by utilizing new technologies other than SiOx and Si-C.

Demand for silicone anode material is expected to grow at a CAGR of 50% from 2019 to 2030 in accordance with needs from vehicles and battery makers, reaching approximately 150,000 ton in 2030. Its main use is expected to expand from IT application to electric vehicles.

Table 11 List of Silicone Anode Material Developer/Manufacturer

No	Country	Company
1	China	Shanshan
2	China	BTR
3	Korea	Daejoo Electronic Materials
4	Korea	NEO Battery Mateiral
5	Korea	Iljin Electric
6	Korea	LPN
7	Korea	NMT
8	Korea	MK Electron
9	Korea	EG Corporation
10	Korea	Hansol Chemical
11	Korea	TRS
12	Korea	FIC Advanced Materials
13	Korea	KMS (Korea Metal Silicon)
14	Korea	Dongjin SemiChem

15	Korea	Tera Technos
16	Japan	Shin-Etsu
17	Japan	Osaka Titanium Technologies Co., Ltd.
18	US	Group 14
19	US	Sila Nano
20	US	Enovix
21	US	Enevate
22	US	Enertech
23	US	EoCell
24	US	Amprius
25	US	Nanotek
26	UK	Nexeon
27	Netherlands	E-magy
28	Germany	Wacker
29	Norway	Elkem(Silgrain power)
30	Netherlands	Leyden Jar
31	US	Sionic
32	Germany	Wacker

3.3 Separator

The separator for lithium secondary batteries is a micro pore membrane. Looking at the main properties in the table below, its thin membrane is about 10-25μm, and its micro-porosity has a pore size of 10-500 nm and an air porosity of 30-60%. The role of separator can be largely explained as follows: 1) preventing electrical short-circuit between the two electrodes and 2) providing a path for ion transfer so that the electrochemical reaction can proceed continuously. In this regard, the battery performance and the physical factors of the separator have a very close correlation.

Table 12 Major Properties of Separator for Lithium Secondary Battery

Item	Unit	Content
Thickness	μm	5-25
Pore Size	nm	10-500
Porosity	%	30-60
Air Permeability	sec/100ml	< 650
Puncture Strength	g_f	> 350
Tensile strength	MPa	~ 100

The air-leakage characteristics come to be influenced by the Gurley Number, in accordance with the thickness, air porosity, pore size and distribution, and curvature degree of the separator. Particularly, the Normalized Gurley Number converted into the separator thickness has a strong correlation with the Ionic Conductance; the rate capability of the battery is greatly affected by this factor value. Of course, the absolute value of battery performance may vary according to the electrolyte or the selection of electrodes, but it has been reported that under the same conditions, the Normalized Gurley Number or Ionic Conductance is important. Therefore, the selection of an appropriate separator has a very important effect on the overall battery characteristics, including energy density, power density, life characteristics, safety, etc.

In addition, the materials used for the separator should be electrochemically stable enough not to participate in the reaction within the battery; their costs should be also selected from among the considered materials. Various separators can be utilized depending on the battery types and systems; yet, in lithium secondary batteries, unlike separators applied in other batteries, as the development has been mainly performed on polyolefin-based resins. Currently, most of the commercialized products are using polyolefin-based materials, such as polyethylene, polypropylene, or polyethylene/polypropylene composite layer. However, since the heat resistance limit due to the low melting point of polyolefin materials is clear, materials with excellent heat-resisting property, such as Polyethylene Terephthalate (PET), Polyacrylonitrile (PAN), Polyimide (PI), Cellulose, etc. are spun and then, used in the form of a non-woven base film. There have been also attempts to overcome the limitations of polyolefin materials by introducing organic/inorganic composite layers.

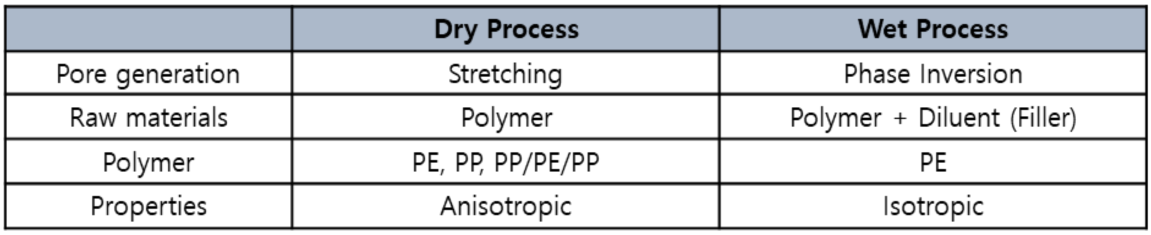
As price pressure for mid- to large-sized lithium secondary batteries continues, the demand for lowered prices of separators is also greatly increasing. In particular, the price pressure refers to the situations where we should 1) prepare measures to reduce raw materials and process costs, 2) increase the production yield rate by reducing the defective rate, and 3) overcome it with economies of scale by increasing production. Therefore, for the continuous expansion of lithium secondary batteries, it is essential to develop a high-performance/lower-priced separator.

(Types of Separators)

Separators for lithium secondary batteries can be classified into various types, according to their physical/chemical characteristics. Specific examples thereof include Microporous Membranes, Wovens, Nonwovens, Paper, Laminates, etc. In most of commercialized batteries, microporous membranes, nonwovens, or the like are used as separators; particularly, in lithium secondary batteries, microporous membranes account for the most part in consideration of the battery assembly and performance characteristics.

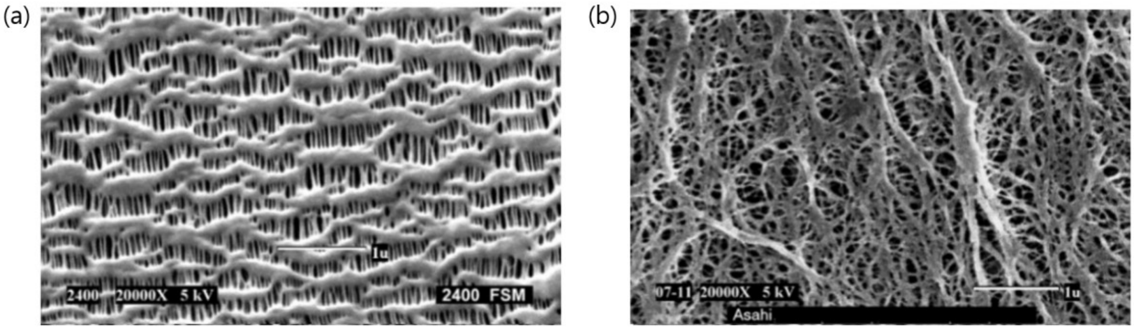
The manufacturing process of separators for lithium secondary batteries can be largely divided into a Dry Process known as an elongation-opening method and a Wet Process based on phase separation and extraction. Both methods consist of an extrusion process for forming films and a porous process for forming pores. In most of the extrusion, a twin-screw extruder is used, but a single-screw extruder is utilized when a manufacturing method not requiring polymer blending or polymer and solvent mixing is employed. Both the wet and dry processes involve the processes of ejections to form thin membrane-like polymers and stretching to form porous structures. There are 2 methods: a uniaxially-oriented method stretching only toward the MD (Machinery Direction) and a biaxial-oriented method stretching toward the MD and TD (Transverse Direction), when elongating the sheet extruded in a T-die. Compared to uniaxially-oriented films, since biaxial-oriented films have high strength and isotropic properties, they have desirable properties as a separator. The method that the tubular elongation is performed after being extruded in a circular die is also used. There is a difference in the manufacturing method, but the pore morphologies are also different. The separator made through the dry process shows the anisotropic pore structure, whereas the separator made through the wet process exhibits the isotropic pore structure. A table comparing the dry and wet processes is shown in the table below.

Table 13 Categorization of Separator by Manufacturing Process



	Dry Process	Wet Process
Pore generation	Stretching	Phase Inversion
Raw materials	Polymer	Polymer + Diluent (Filler)
Polymer	PE, PP, PP/PE/PP	PE
Properties	Anisotropic	Isotropic

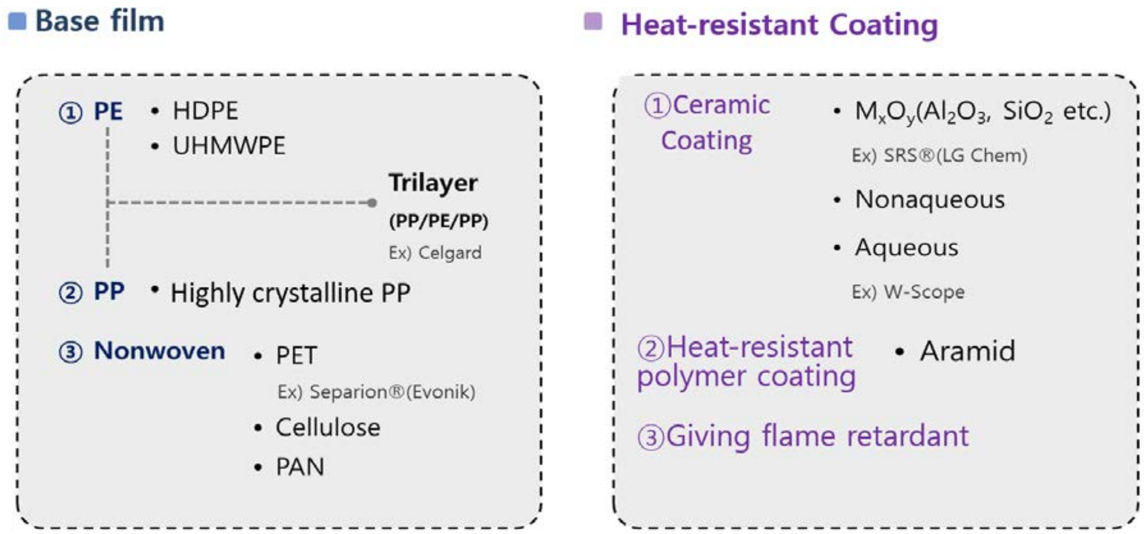
Figure 16 Porosity comparison according to separator manufacturing processes: (a) Dry Process (b) Wet Process



(Latest Technology Trend for Separator)

In case of the separator made based on the conventional commercialized polyolefin materials, it melts at about 130-170℃ and accordingly, its mechanical strength rapidly drops when exposed to high temperatures, and it comes to have fluidity, finally resulting in material contacts between cathodes and anodes, which will lead to ignition and explosion of the battery. Therefore, the method for improving safety is to enhance the thermal properties of the separator; thus, when the temperature inside the battery rises rapidly due to abnormal operation inside/outside the battery, it is of utmost importance that the separator’s material isolation between cathodes and anodes should be constantly maintained so that this may not lead to ignition or explosion of the battery. Looking at the recent research trend, in order to improve the performance of the existing polyolefin, attempts have been continuously performed to increase the thermal stability of the separator by introducing inorganic substances or heat-resistant polymers or by designing the separator with a multi-layer structure.

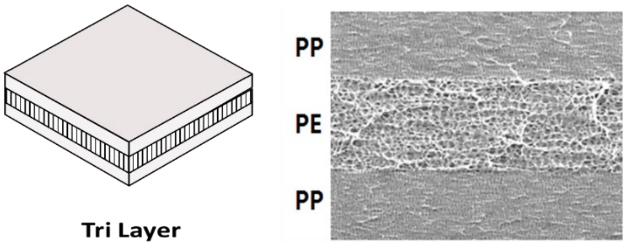
Figure 17 History of heat-resistant separator technology



1) Multi-Layered Heat-Resistant Separator

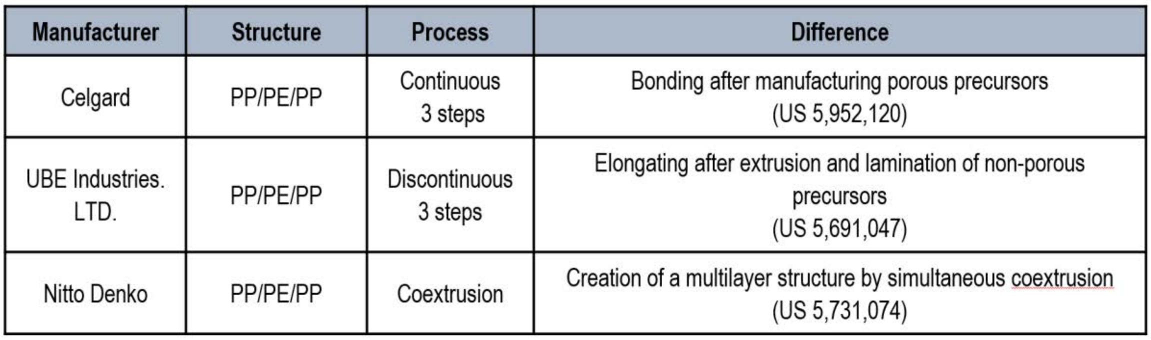
Largely, in terms of Base films, Celgard has ever released a product that the shutdown and thermal shrinkage phenomena of the separator were improved by comprising the Trilayer of PP/PE/PP while equally using the existing polyolefin-based. Figure 18 shows the schematic diagrams and cross-section of Celgard's PP/PE/PP multi-layered separator. After placing PP layers on the outside and a PE layer in the middle, the Celgard's multi-layered separator is manufactured by bonding them, where the PP layer plays a role of improving the mechanical integrity characteristics and the oxidation stability on the electrode surface and the PE layer provides the shutdown characteristics.

Figure 18 Celgard's PP/PE/PP Multi-Layered Structure Separator [11]



Major dry-separator manufacturing companies, other than Celgard, are also manufacturing separators where the multi-layered structure is introduced; the structure and process of each company's separator are shown in the table below.

Table 14 Manufacturers and features of multi-layered structure separators



Manufacturer	Structure	Process	Difference
Celgard	PP/PE/PP	Continuous 3 steps	Bonding after manufacturing porous precursors (US 5,952,120)
UBE Industries. LTD.	PP/PE/PP	Discontinuous 3 steps	Elongating after extrusion and lamination of non-porous precursors (US 5,691,047)
Nitto Denko	PP/PE/PP	Coextrusion	Creation of a multilayer structure by simultaneous coextrusion (US 5,731,074)

2) Non-Woven Separator

In case of using a polyolefin-based material, the limit on the heat resistance of the material itself still exists and thus, development cases and studies using materials with excellent heat resistance have been published. In addition to securing safety, the next-generation separator is also requiring its inexpensiveness. The method to solve this problem is applying the nonwovens to a separator for lithium secondary batteries; as the production of Nano-level fibers has become enabled, it also became possible to produce nonwovens with the thickness lowered to the level of polyolefin separators. Japan's Hirose Paper can produce PE/PP multi-layered fibers by using the electrospinning technology that does not need a nozzle, so if they are made of nonwovens, they can be used as a separator for lithium secondary batteries; the low-cost separator using polyacrylonitrile (PAN) nanofibers developed by Nippon Vilence can reduce the nanofiber diameter up to about 350nm, it has an advantage that the thickness of the nonwovens manufactured using this can be secured to the extent of the level of the polyolefin separator.

As a material to secure price competitiveness by making it with nonwovens, Cellulose materials are being used because they are cheaper than other materials; yet, considering the fact that lithium secondary batteries are driven over 4V and that $LiPF_6$ lithium salt, weak in moisture, is used, moisture management within cellulose could be thought of as the key to the success of the separator.

3) Inorganic Material-Introduced High Safety Separator

The most reliable way to achieve high safety of the separator is to introduce inorganic materials. The inorganic-coated separator (or ceramic-coated separator) exhibits very excellent wetting properties for electrolytes due to its high hydrophilicity and large surface area, expressing excellent thermal stability even at high temperatures. In the meantime, many cases have been reported on inorganic substance-coated separators (or ceramic-coated separators) that have greatly improved heat resistance by introducing inorganic matters into the separator or coating them on its surface.

Asahi Kasei is a company that has introduced inorganic substances into the separator, and Litarion (Evonik, Degussa) is a representative company that has introduced them on the surface of the separator. Litarion has ever utilized Al_2O_3 and SiO_2 on the surface and inside of the PET nonwoven to control the pore structure and improve its heat resistance by introducing organic/inorganic composite layers.

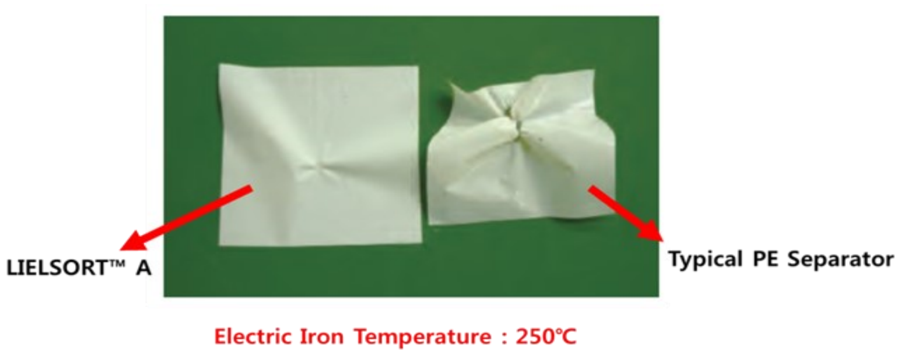
In case of high-safety separators through the introduction of inorganic substances, they can be largely classified into two types depending on the type of solvent for the coating slurry: 1) non-aqueous system and 2) aqueous system.

4) Heat-Resistant Polymer-Coated Separator

Another way to overcome the limitation of introducing a ceramic coating layer based on slurry is to exclude the use of ceramic and apply only heat-resistant polymers as a coating material. The method of coating a heat-resistant polymer not only has the advantage of using the existing polymer coating process, but also can resolve the problem of increased unit costs and difficulty in the battery assembly process, according to the introduction of ceramics.

An example for a representative commercialized product is Teijin's LIELSORT™ A, which was manufactured by coating Meta-Aramid on a porous substrate. Due to its porous structure, Meta-Aramid minimized the deterioration for the air-permeability feature of separators and improved the mechanical properties and electrolyte wettability. Moreover, since having no melting point, it has the advantage of being able to improve all the thermal safety, puncture strength, etc.

Figure 19 Teijin′s heat-resistant polymer-coated separator (LIELSORT™)



Even in recent papers, there have been studies attempting to improve the heat resistance and electrochemical performance of separators by using various high heat resistant polymer binders. First, it is an example of coating hydrophilic polydopamine polymers on the surface and inside of the separator. The separator can be coated through a simple process of impregnating the separator after preparing the pH 8.5 dopamine solution; the hydrophilicity of the separator can be greatly increased by directly coating the surface and inside of the separator. In addition, since it is coated into several to tens of nanometers, it has the advantage of not lowering the air permeability of the separator and of improving the heat resistance and adhesion. With these advantages, polydopamine is widely applied to other materials, such as electrodes, electrolytes, etc., as well as separators.

Second, this is an example of coating a polyethylene separator with high heat-resistant polyimide (Co-polyimide, P84). Due to the high melting point and thermal resistance of polyimide, the thermal stability of the separator was improved without introducing ceramic. In addition, by controlling the coating morphology of polyimide into a spherical particle shape, the deterioration of the air permeability of separators was minimized.

Polymers with excellent heat resistance have disadvantages that the solubility in solvents is significantly lowered and that material prices are high. Accordingly, development of low-cost heat-resistant polymer materials, which have excellent heat resistance and have dissolution properties applicable to the coating process, will continue to be required.

Table 15 Global Production Capacity Trend and Forecast by Major Separator Makers

[Unit: Mil. m^2]

Supplier	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
SEMCORP	43	120	259	1,835	2,850	3,000	4,970	5,670	6,950	7,670	8,220
SKIET	250	250	300	350	520	860	1,360	1,530	2,200	2,870	3,920
Asahi	455	515	680	683	885	1,057	1,342	1,522	1,751	2,045	2,424
Senior	135	165	295	315	695	1,195	1,195	1,195	1,555	2,255	2,255
Sinoma	30	60	120	720	960	1,608	1,848	1,848	1,848	1,848	1,848
Toray	180	220	300	468	522	576	666	792	919	1,082	1,298
W-scope	130	200	280	400	560	560	680	680	737	807	890
CZMZ	38	75	135	340	390	440	490	490	490	490	490
Others	845	1,233	2,135	4,674	5,779	7,159	8,005	8,919	9,211	9,912	10,121
Total	2,106	2,838	4,504	9,785	13,161	16,455	20,556	22,646	25,661	28,978	31,466

(Global Production Capacity Trend and Forecast by Major Separator Makers)

The separator market has been steadily oversupplied, mainly by low-tier companies, but as the market is arranged, supply is on the decline after peaking in 2020. The oversupply situation is expected to gradually dissipate as the low-priced dry separator market shrinks and the market stabilizes. Due to a surge in demand in the future, there is a possibility of a separator supply shortage, and a shortage is expected after 2024.

Table 16 Global Separator Market Demand Outlook (2019-2030) [Unit: 0.1Bil. m^2]

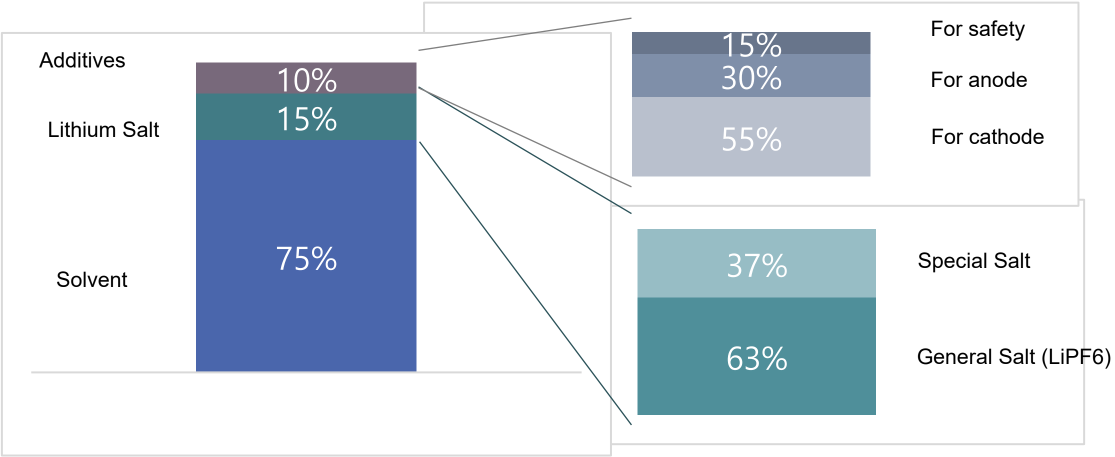
Demand	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	CAGR
Total	40	41	55	82	106	132	159	183	209	240	275	316	20%
Wet	26	27	37	56	73	92	113	133	155	182	214	252	22%
Dry	14	14	18	26	33	40	45	50	54	58	61	64	13%

3.4 Electrolyte

When it comes to the composition of electrolyte, it consists of Solvents, Lithium salts, and Additives. Due to its characteristics, electrolytes should be developed, jointly with Li-Ion secondary battery manufacturers. In the case of IT-type small products, it will shortly take a development period of 3-4 months, and for the electrolyte for xEV, the development and evaluation should be conducted for over one year.

Lithium salts (LiPF6), a major component of electrolyte, are supplied, up to about 80%, by Japanese 3 companies, and Korean Foosung mass produces and supplies Lithium salts (LiPF6) as the only company in Korea. Additives are added during the process of producing electrolytes, in order to improve the lifetime and stability of the Li-Ion secondary batteries, by performing activities, such as formation of SEI protective films, addition of overcharge inhibitor, and improvement of conduction property.

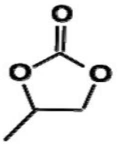
Figure 20 Use Amount of Major Materials for Electrolyte (As of 2019)

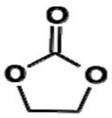


1) Cyclic Carbonate

The organic solvent constituting the electrolyte is composed of cyclic and linear carbonates. Cyclic carbonate can dissociate lithium salt more easily because of its higher permittivity than linear carbonate. However, due to its high viscosity, it cannot be used alone; it should be used after mixing linear carbonates which have a lower viscosity despite its relatively lower permittivity.

Figure 21. Structure of cyclic carbonates; (a) PC and (b) EC





(1) Propylene Carbonate (PC)

As the cyclic carbonates are decomposed during the charging process, they form the SEI membrane on the surface of anodes; in the case of ethylene carbonate (EC), the SEI membrane is densely formed, which can prevent the co-intercalation of the solvent. However, since the SEI membrane formed by the decomposition of PC is not effective, a problem occurs that the solvent is co-intercalated. That is, the PC is inserted into graphite, together with lithium ions, and then, the graphite is exfoliated during the process that the lithium ions are desorbed.

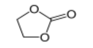
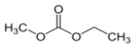
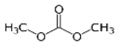
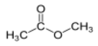
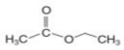
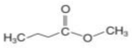
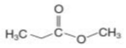
(2) Ethylene Carbonate (EC)

EC, exhibiting a high permittivity (ε=90), has been used as a main solvent for dissociating lithium salts into lithium cations and anions in the electrolyte to form an electric charge source.

2) Linear Carbonate

Linear carbonates (DMC, EMC, and DEC) have a low viscosity, thus functioning as a low-viscosity ion-conducting medium that helps lithium ions dissociated by the high dielectric constant in the electrolyte solution, due to their low viscosity, to move smoothly between the anode and cathode in the electric field. For this reason, the electrolyte solvent is produced with a blending composition of a high dielectric constant solvent and a low-viscosity solvent. As shown in Table 17 since DMC (viscosity = 0.59cP), one of linear carbonates, is superior in its ability to make a low-viscosity electrolyte to EMC (viscosity = 0.65cP), when applied to the battery where high-cladding electrodes are utilized, it could be expected that the immersion property of the electrolyte would be improved and the penetrating force and dispersibility of the electrolyte inside the electrodes would be enhanced. In addition, DMC at a temperature below room temperature has a lower viscosity than EMC, which is effective in improving the low-temperature output property of the battery. However, since the melting point of DMC is 4.6℃ higher than 0°C, there might be a limitation in reducing the viscosity of the electrolyte at low temperatures below 0°C.

Table 17 Melting point, fusion point, and viscosity at room temperature in linear carbonate solvents [12]

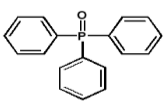
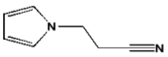
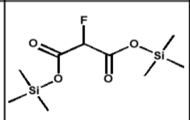
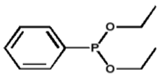
Name	Melting point (°C)	Boiling point (°C)	Viscosity at 25°C (cP)	Dielectric constant	Structure
Ethylene carbonate (EC)	36.4	248	1.93 (40°C)	89.8 (40°C)	
Ethylmethyl carbonate (EMC)	-53	110	0.65	2.958	
Dimethyl carbonate (DMC)	4.6	90	0.59	3.107	
Methyl acetate (MA)	-98	57	0.40	6.68	
Ethyl acetate (EA)	-84	77	0.46	6.0	
Methyl butyrate (MB)	-85.8	102.8	0.541	5.48	
Methyl propionate (MP)	-87.5	79.8	0.431	6.20	

(Electrolyte Additives)

(1) Electrolyte Additives for High-Ni-based Cathode Interfacial Stabilization

The energy density will increase as the Ni content in cathode material increases higher. Recently, a growing need for cathode material of which Ni content is over 80% has been witnessed in order to realize the high-energy densification of batteries. Some of the examples are introduced in Table 18 as follow.

Table 18 Oxidative decomposition type additives for interfacial stability of high-Ni-based cathode-electrolyte and acid material trapping additives in electrolytes

Additive function	Additive name	Structure	Battery driving conditions	References
· HF scavenging Film building on anode	Triphenylphosphine Oxide 0.5 wt% (TPPO)		2.8-4.3V @ RT NCM811/Graphite Full cell	Chem. Mater. 2018, 30, 2726
Stabilization of LiPF6 HF Scavenging Oxidative decomposition mechanism Discharge rate characteristics	1-(2-cyanoethyl) pyrrole 1 wt% (CEP)		3.0-4.5V @ RT NCM622/Graphite Full cell	J. Phys. Chem. Lett. 2018, 9, 3434
· HF scavenging	Bis(trimethylsilyl) 2-fluoromalonate 5 wt% (BTMSMFM)		NCA/Li half cell	Journal of Power Sources, 2019, 412, 527
· HF scavenging	Diethyl phenylphosphonite 2 wt%(DEPP)		3.0-4.35V @RT NCA Half cell	J. Mater. Chem. A, 2018, 6, 16149

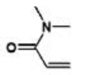
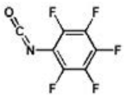
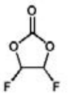
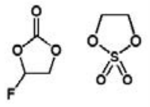
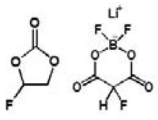
(2) Electrolyte Additives to Improve Output Characteristics

$LiPO_2F_2$ exhibits the behavior of reductive cleavage in the reductive atmosphere supplied with electrons and lithium. The starting potential of reductive cleavage reactions of $LiPO_2F_2$ is slightly lower than that of VC. The cleavage products (compounds containing P-O and P-F polar groups) formed by this reduction cleavage reaction may perform the SEI function to protect the surface of anodes by being physically deposited on the surface of anodes. However, when using $LiPO_2F_2$ alone, since it makes the SEI components unable to remain stable on the surface of anode in the delithiation of lithium ions, a technique is necessary to use together with the reductive cleavage type additive that can form polymer components to connect these SEI components. By using it with the VC which can form polymer components, forming the composites of compounds containing polar groups of polymers will help to protect the anode surface and simultaneously to maintain the SEI structure during high-speed discharging.

(3) Electrolyte Using LiFSI Salt

The electrolyte containing LiFSI salt shows higher ionic conductivity than $LiPF_6$. This is because, as can be seen from the structure of the LiFSI salt, the binding energy between the FSI anions and the lithium cations is relatively lower than that of the $LiPF_6$ salt and because LiFSI salts can be easily dissociated at the same salt concentration and in solvent composition to generate a high content of charge. This high ionic conductivity of LiFSI may contribute to the improvement of fast charging performance. We can recognize that its constant current (CC) section is longer and its discharge capacity is higher than those of $LiPF_6$ under fast charging conditions. Shortening of the CC section and increasing of the CV (constant voltage) section will not be preferable because reversible capacity loss may be induced by side reactions of the electrolyte at the cathode and anode and metal lithium precipitation may also be caused.

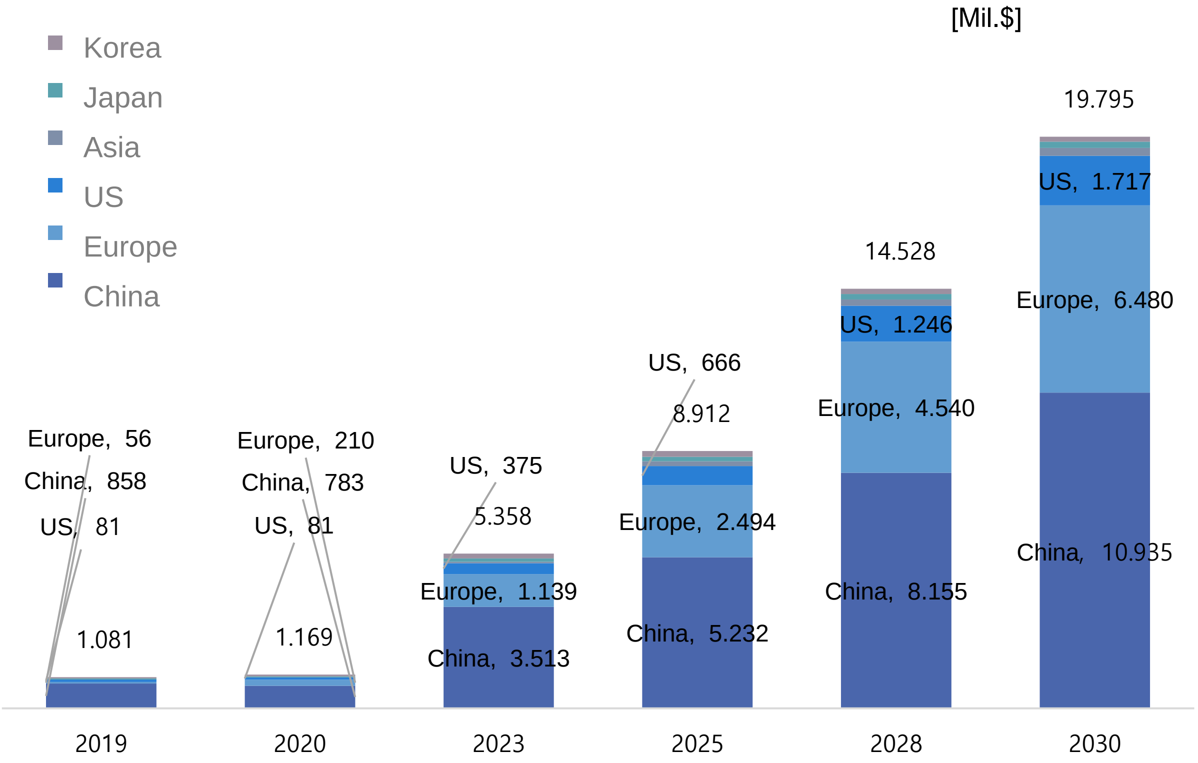
(4) Additives for Interfacial Stabilization of High Capacity Anode

Additive function	Additive name	Structure	Battery driving conditions	References
· PF_5 scavenging · Capacity retention : 80% or more (@500 , 0.2C) · Discharge rate characteristics : 31.8% @ 20C	Dimethylacrylamide 2.5 wt% (DMMA)		Si nanoparticle half cell 0.01−1V @RT	RSC Adv., 2019, 9, 435
Silicon cathode SEI formation Contribution to cathode CEI formation	Pentafluorophenyl Isocyanate 2 wt% (PFPI)		Si thin film/NCM111 full cell 3.0−4.3V @20℃	ACS Appl. Mater. Interfaces 2018, 10, 28187
SiO-C composite anode SEI formation · Capacity retention : 83.9% (@500 times, 1C)	4, 5-difluoro-1, 3-dioxolan-2-one 2 wt% (DFEC)		$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$/SiO@C full cell 2.75−4.2V @RT	Journal of Electroanalytical Chemistry, 2019, 834, 1
SEI formation by FEC and PCS (LiF + organic surfites, sulfates) Gas generation suppression (DEMS analysis)	Fluoroethylene carbonate 1 wt% (FEC) 1,3-propanediolcyclic sulfate 1 wt% (PCS)		SiO_x-C/ $LiNi_{0.5}Mn_{1.5}O_4$ full cell 3.5-4.9V @RT	Chem. Mater. 2018, 30, 8291
Complement of mechanical materi al-properties of anode SEI by FEC High voltage Li-rich cathode CEI fo rmation	Fluoroethylene carbonate 5 wt% (FEC) & Lithium fluoro malonato(difluoro) borate 1 wt% (LiFMDFB)		2.0-4.55V @RT SGC(Si-graphite composite) /$Li_{1.17}Ni_{0.17}Mn_{0.5}Co_{0.17}O_2$ Full cell	Energy Environ. Sci., 2018, 11, 1552

(Electrolyte Market)

The electrolyte market is expected to grow at a CAGR of 33% from 83,000 ton in 2019 to 2,084,000 ton in 2030. Based on price, it is expected to expand from US$ 1 billion in 2019 to US$ 20 billion in 2030. The electrolyte market by region is shown in Figure 22 below.

Figure 22 Forecast on Electrolyte Market by Region



The supply of electrolyte is expected to increase from 253 kton in 2019 to 849 kton in 2025. According to interviews with major electrolyte companies, given the operation rate and yield rate compared to design capacity, the expected production quantity is approximately 70% of the design capacity.

Table 19 Forecast on Capacity of Major Electrolyte Companies

(Unit: kTon)

	2019	2020	2021	2022	2023	2024	2025
Tianci (China)	28	46	60	70	98	126	140
Capchem (China)	46	60	74	81	92	126	140
Huarong (China)	21	49	56	63	63	70	105
Shanshan (China)	25	25	49	49	70	84	105
Enchem (Korea)	18	32	53	74	74	74	74
Central Glass (Japan)	25	25	25	35	35	35	56
Mitsubishi (Japan)	32	32	32	49	49	49	56
Kunlunchem (China)	20	20	34	34	34	34	34
Soulbrain (Korea)	11	14	18	21	25	25	35
Donghwa (Korea)	22	28	28	28	28	28	35
Others	7	21	35	35	56	56	70
Total	253	351	463	539	623	706	849

3.5 Module/Pack[13]

Battery pack consists of various components: battery cell, module, thermal management part, housing, connecting components, sealant, module case, and electronic components.

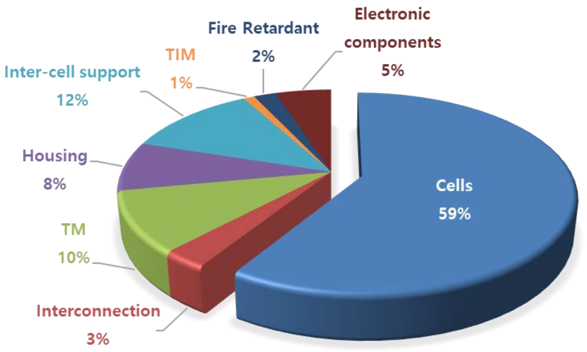
Table 20 Comparison between Cell, Module, and Pack

Item	Components	Description
Pack	Case (metal), BMS, cable, cooling system	Pack is made with several modules connected with each other, together with sensor, BMS, and housing.
Module	Case (metal, plastic), cooling system, ICB	Module is made with several cells that are connected to each other before placed in a metal or plastic case.
Cell	Electrode active material, liquid electrolyte, separator, current collector, case (pouch, prismatic, cylindrical, button)	A single cell that can be charged with electricity and discharged

Battery packs use different types of batteries: cylindrical, prismatic, and pouch types. Cooling systems also vary from air-cooling, water-cooling, and refrigerant-cooling. Figure 23 shows the component ratio of each major component based on types and weight of components used inside a battery pack.

Figure 23 Ratio of Weight by Battery Pack Component

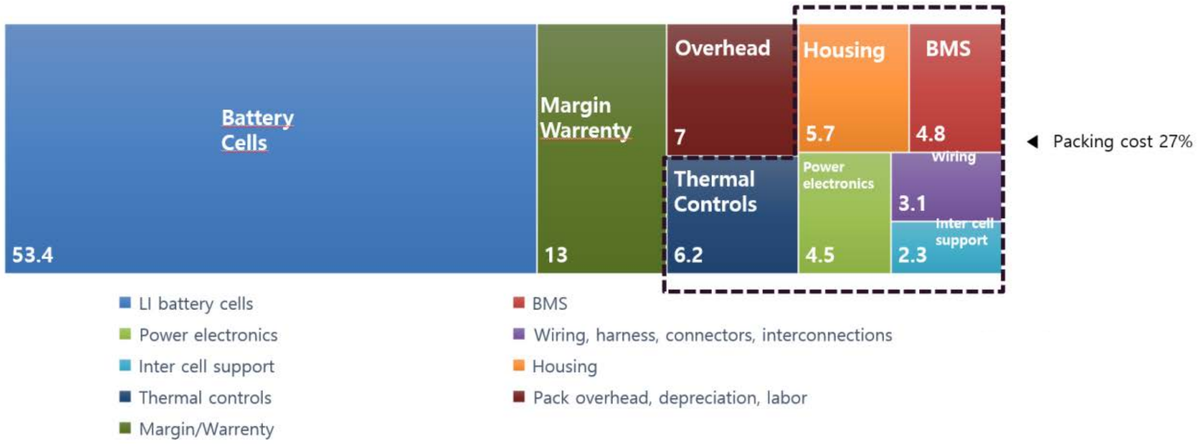
Intercell structural components	Compression pad Insulation pad Cell holders Sealing
Module-connecting components	Busbar HV cables
Electrical and Electronics Components	PRA MSD BMS



Within the cell category, only battery cell is included. Thermal management components here refer to pumps, hoses, and other heating and cooling components. As seen in the above Figure 23, if cell is not counted, the improvement of energy density of pack can be achieved by enhancing heat management, intercell components, and housing.

The structure of production cost for battery cell is shown in Figure 23 below.[14] Battery cells take up more than 50% of the entire cost, while the margin (incl. warranty) for pack production accounts for 20%. The ratio of components used to make a pack reaches around 27%. However, the ratios shown below may change depending on materials used by battery makers and car OEMs (who design their battery pack) and the processing method used for those materials.

Figure 24 The Occupancy Ratio of Each Component (based on the total pack cost to be 100)

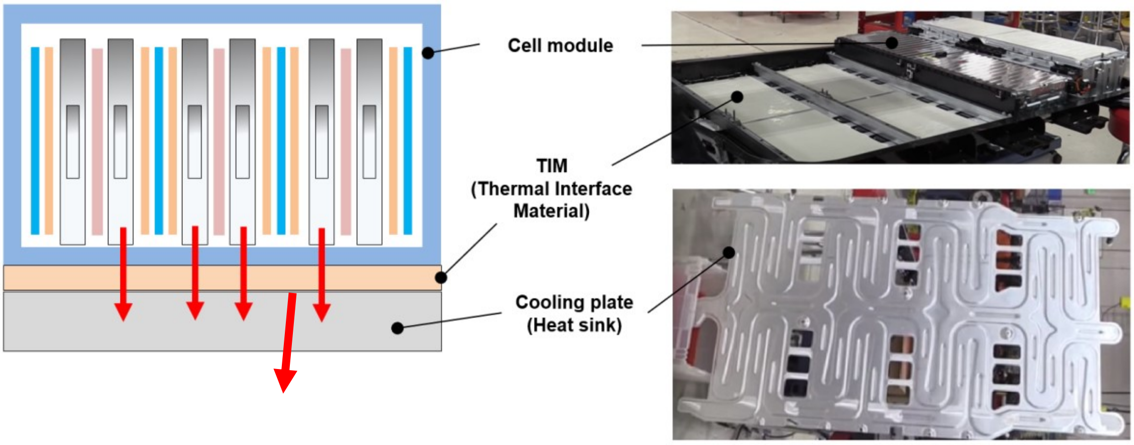


(Features of Major Components inside Pack)

(Thermal Managing Parts)

Thermal interface material (TIM) refers to a material applied to heat sink (cold plate) in order to transfer the heat easily from parts where heat is generated. As shown in the below image, TIM is used to remove air gaps between heat sink and cell module and to make an even contact with parts where heat is generated.

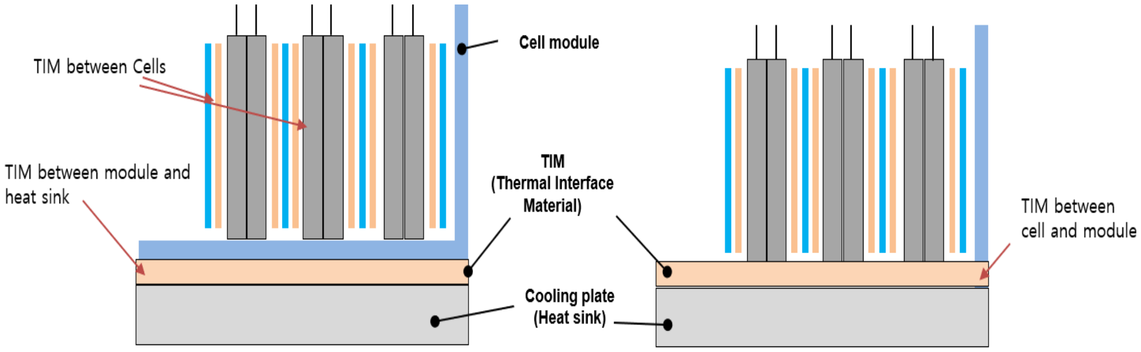
Figure 25 Example of application of TIM



TIM, located between aluminum-based heat sink and battery module, is usually used as heat transferring path. It must have adequate compressive strength to maintain mechanical strength during operation. It has to satisfy flame retardant grade (UL94 V-0 grade). Silicone, Acrylic, and PUR are used as materials, and there are pad type and liquid dispensed gap filler. Gap pad TIM is used between cells and between cells and modules or between module housing and heat sink. Gap pad material provided by 3M gap pad has thermal conductivity of 2.0W/mK and flame retardancy of UL 94V-0.

Since the gap pad is filled with thermally conductive filler and materials have different compression state, it is very important for module or pack manufacturers to accurately determine the gap to fill TIM. In fact, thermal conductivity value may vary depending on filling rate of filler and compression rate of TIM. Since the value may be measured differently even for the same materials depending on compressed thickness, right thickness of TIM should be determined in accordance with the design requirements.

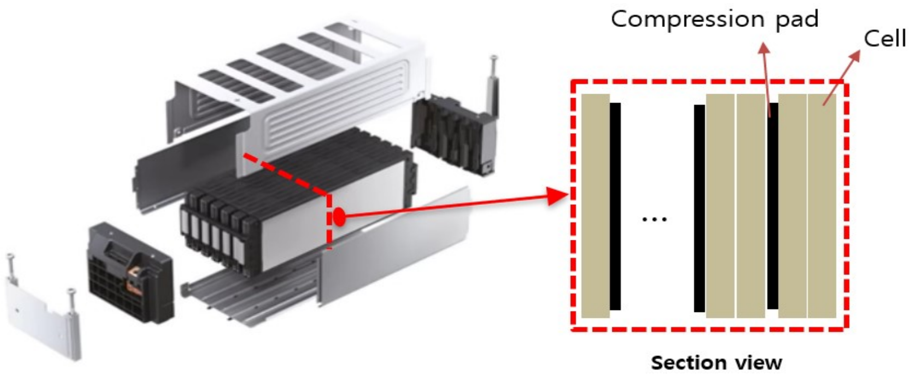
Figure 26 Example of Gap Pad Type TIM



A notable trend in the industry is moving from gap pad to liquid dispensed filler (gap filler). The main reasons are that smaller amount can be used, reduction in weight and cost is possible, and special shapes and designs are possible. Particularly, liquid filler method can make more close contact with module than gap pads method.
High initial investment cost is disadvantage, and it is important to consider tolerance of dispensing thickness. Careful consideration is needed for viscosity, weight, vertical dispensing, and accurate mixing.

Compression pad is located between cells, and it is a component to protect cells and to maintain rigidity of module structure by absorbing impact when cell swelling occurs. Swelling happens only to pouch cells, whileprismatic and cylindrical types that are surrounded by metal cases do not have swelling. Polyurethane (PUR) foam material is mainly used, and electrical insulation and flame retardancy (V-0) are required. Low permanent compression joint rate (5%) and resilience performance are important. Considering swelling force and displacement of cells, pads need to have appropriate thickness and compression set, for which it is important to check the FTC curve according to compression rate of the pad and select the initial compression rate of the pad.

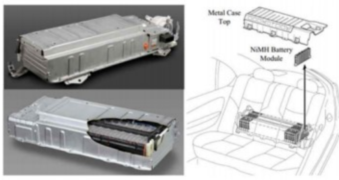
Figure 27 Examples of Compression Pad



(Battery Pack Housing)

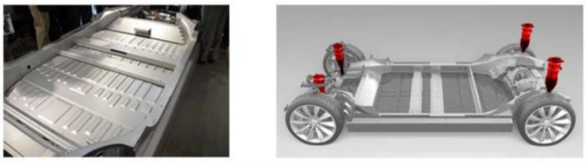
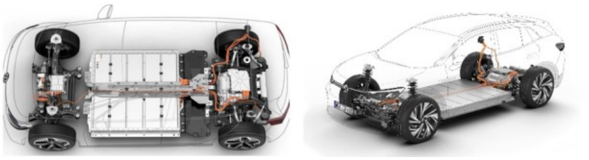
Early models of electric vehicles were manufactured from existing platforms of internal combustion engine vehicles after modification, not EV-only platforms. As a result, space that battery packs have to occupy was very much limited. In most cases, battery pack was located under rear seats or in trunk space. And thin steel sheet was used for pack-housing material. In case of pack shape that has height difference due to depth, as illustrated in Figure 28, injection method by using engineering plastic was mainly adopted

Figure 28 Example of Pack Layout for Early EV Models

Vehicle	Pack layout	Specification
Toyota Prius HEV		Weight: 41kg Size: 297 * 590 * 107 mm Material: Steel press
HKMC Sonata HEV		Weight: 42kg Size: 211 * 353 * 726 mm Material: Galvanized steel sheet
GM Spark EV		Weight: 254kg Housing size: 150 * 110 * 235 mm ,25kg Material: Glass fiber reinforced composite material

Global OEMs recently created dedicated platforms that enabled standardization of battery modules and packs. They are flat, they take form of a snow-board and they are located under the floor. Al material was used to reduce weight. Pack housings are manufactured in the methods of extrusion, die casting, cut and weld. It is also connected to the chassis part of the vehicle to help improve structural safety, driving performance, and riding experience.

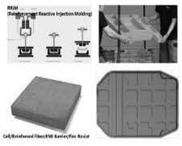
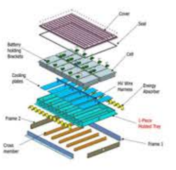
Figure 29 Example of Dedicated Pack Layout

Vehicle	Pack layout	Specification
Tesla Model 3		Standard range 54kWh 381km WLTP Mid range 62kWh 457km Long range 75kWh 614km
HKMC E-GMP Ionic 5		Long range 72.6kWh battery (77.4kWh for NA) Standard range 58kWh battery 800V rapid charge system
VW MEB ID.3 ID.4		modular architecture with up to 12 modules for the full 550 km (WLTP) range 45 kWh (330 km), 58 kWh (420 km), 77 kWh (550 km) operating voltage is up to 408 V

Early EV models such as Mitsubishi Outlander PHEV and Nissan LEAF EV Gen1 mainly used steel as pack housing material. However, there was change to aluminum material due to demands such as lightweight, improvement of pack energy density, and increase in range. Nissan has changed to aluminum material from the 2020 Leaf model. VW used aluminum cover and CFRP tray in e-Golf. For ID models manufactured with MEB platform, they used aluminum case where collision frame is integrated. Even Tesla, which uses steel material a lot in vehicles, used aluminum for battery packs. Various forms of aluminum are being used according to requirements of individual vehicles. For example, in case of Audi e-tron, aluminum was used in battery packs in ratio of 47% extrusion, 36% sheet type, and 17% die casting. Vehicles that have been recently released seem to have used aluminum the most for a battery pack housing material. Battery pack housing by using aluminum extrusion has become a mainstream in the skateboard-type EV platforms such as VW MEB, Hyundai Motors e-GMP, and GM Ultium. Of course, combination with steel can be a good alternative as well.

Battery packs which are composed of battery pack housing and module case take up most of weight in electric vehicles. These days, many companies are developing technology to reduce the weight. Specially, they are adopting battery pack housing using polymer composite material which is a technology to reduce weight by replacing metal. The composite material is used by mixing glass fiber or carbon fiber reinforcing agent with resin such as PP/PA/Polyester/PU.
Battery lower cases (Tray) are being developed into hybrid structure in which metal structure and composite material are fused rather than single composite material to ensure battery capacity and structural safety. It requires bonding technology for heterogeneous materials and integrated molding process technology.

Figure 30 Development of Battery Pack Housing by Utilizing Polymer Composite Material

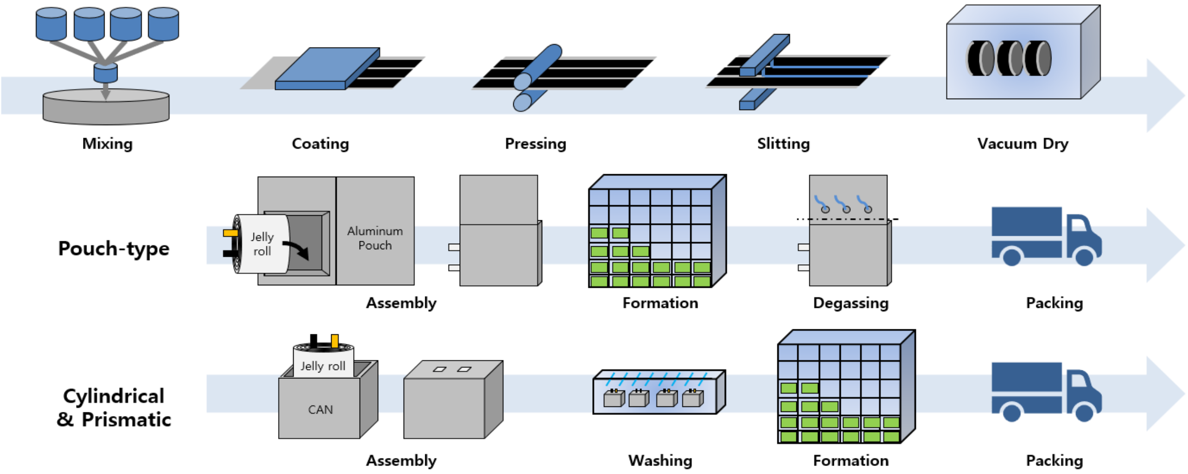
Company	Hanwha Solutions	SGL	BASF	CSP	Audi-Fraunhofer
Pack Shape					
Material	Unsaturated Polyester Resin + Glass Fiber Reinforcement	Multi-layer Carbon Fiber (+Epoxy)	PU-based + Glass Fiber Reinforcement	Non-conductive Vinyl Ester Resin + Glass Fiber Reinforcement	Carbon Fiber, Glass Fiber, PA, Al Composite Material
Process	SMC (Sheet Molding Compound)	Hot Compression Molding	R-RIM (Reinforced Reaction Injection Molding)	SMC (Sheet Molding Compound)	Hybrid Composite Structure (D-LFT, Compression-Insert Molding)
Reduction Rate (as per company announcements)	About 15-20% lighter to previous upper steel cover	40% lighter to aluminum pack cover	50% lighter to pack cover	15% lighter to previous steel-based pack case	42% lighter to previous one

4. Battery Equipment

Secondary batteries are classified by types into pouch, cylindrical, and prismatic types. The secondary battery manufacturing process and manufacturing equipment specifications are changing according to such product types and sizes and the specifications required by customers.

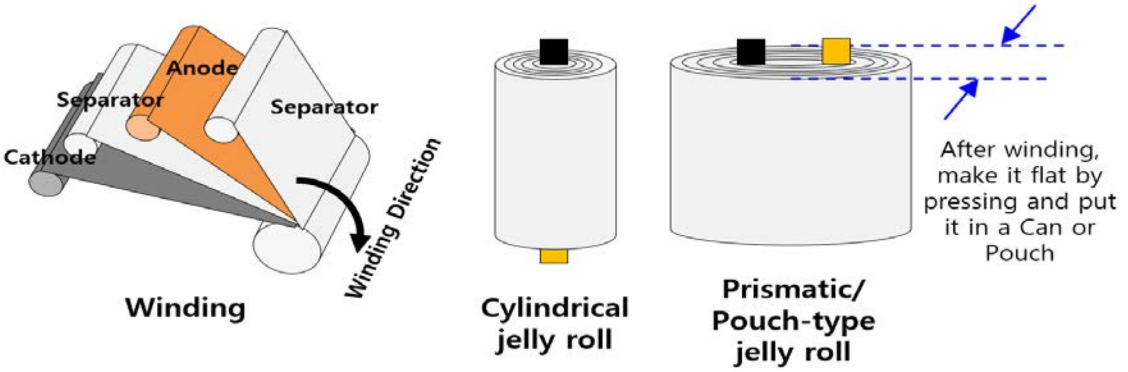
Manufacturing secondary batteries is divided into 3 main processes of Electrode (pole plate) -Assembly – Formation where the electrode and formation processes are typically performed as a similar process regardless of the battery type. Because the pouch-type battery requires a large amount of electrolyte to be injected at once, a lot of gas is generated in the formation process, compared to the cylindrical and prismatic types, so the degassing process is added to get rid of the gas.

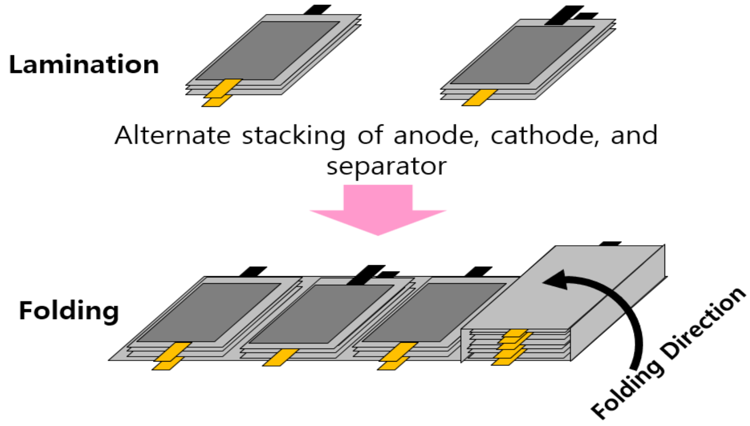
Figure 31 Summary of Secondary Battery Manufacturing Process



After finishing the vacuum drying in the electrode process, the secondary battery is assembled into the structure, consisting of an anode, a cathode, and separators, in the assembly process. The structure can be manufactured (assembled) by diverse construction methods, including Winding, Zigzag Stacking, Lamination & Folding, and Lamination & Stacking.

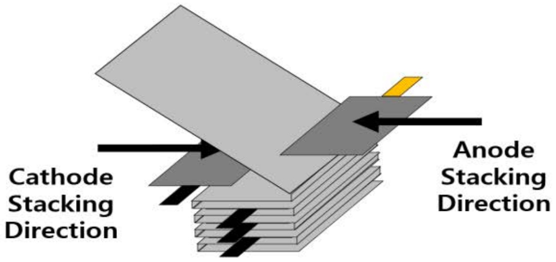
Figure 32 Comparison of production methods of secondary battery electrode structure





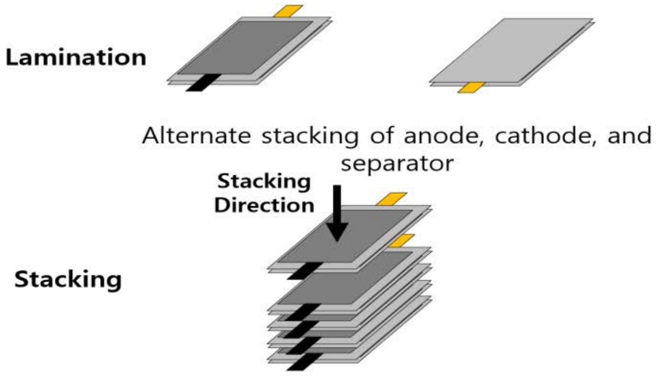
Lamination & Folding
(LGES's patent technology)

Stack/Folding-type cell

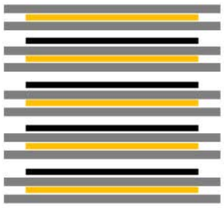


Zigzag(Z) Stacking

Stacking-type cell



Lamination & Stacking
(LGES's patent technology)

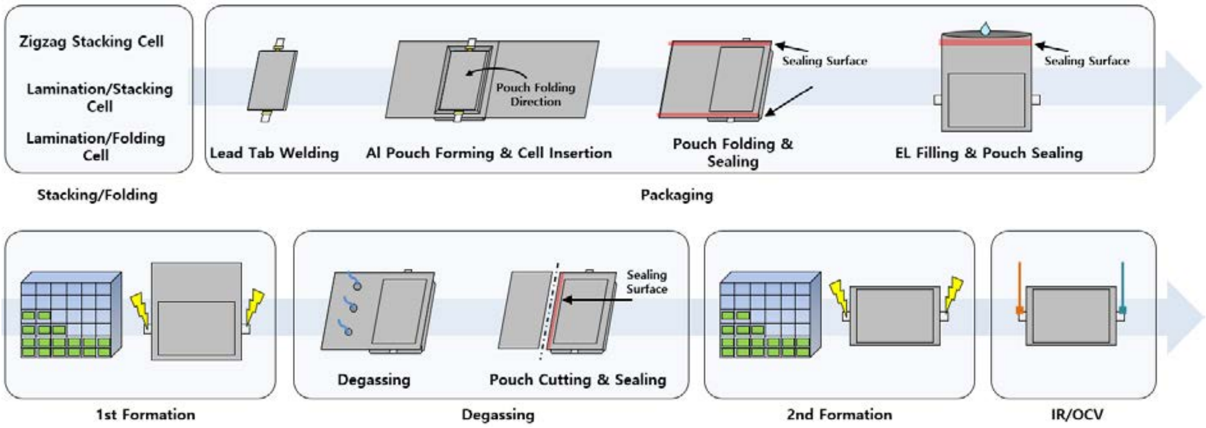


Stack-type cell

4.1 Pouch-type Secondary Battery Production

The structure (cell) fabricated in the stacking or folding method in the previous process is inserted into the pouch after its lead tab welding in the packaging process; then, the electrolyte is injected, and it is first sealed and goes through the primary formation (Formation) process. After that, in the degassing process, the internal gas generated in the primary formation process is removed and then, the characteristics (IR/OCV) are checked after executing the secondary sealing and secondary formation processes.

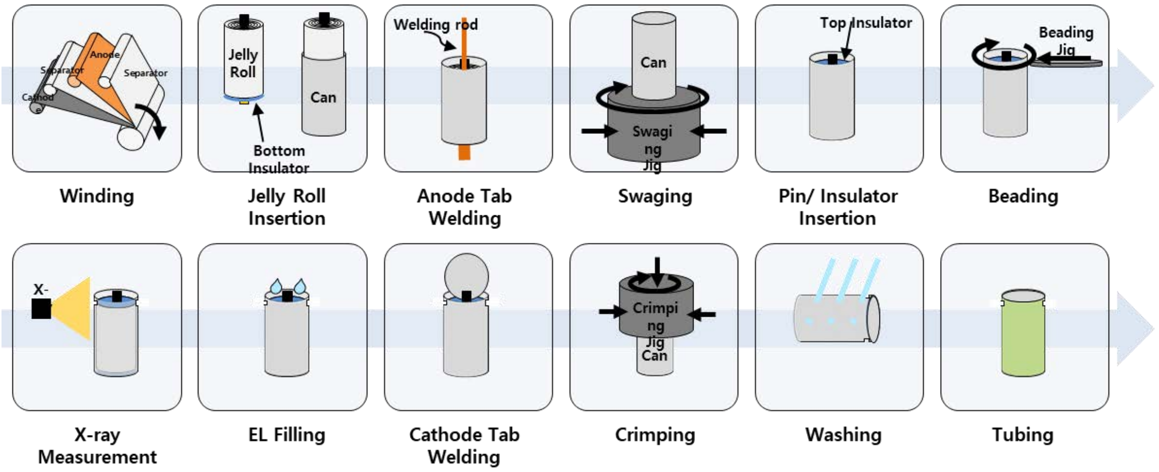
Figure 33 Summary of pouch-type secondary battery assembly process



4.2 Cylindrical Secondary Battery

For the cylindrical battery, after finishing the vacuum drying process in the electrode process, the structure (jelly roll) comes to be manufactured in the winding process. The jelly roll is inserted into the Can; the subsequent Can assembly process and forming process are as follows.

Figure 34 Summary of cylindrical secondary battery assembly process

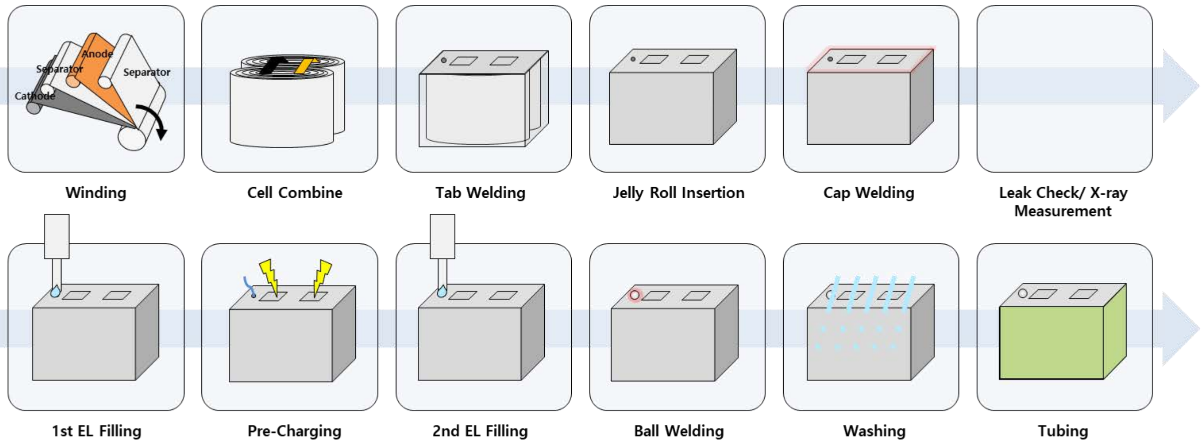


4.3 Prismatic Secondary Battery

As for the prismatic battery, it is common to fabricate a structure (jelly roll) by winding after the vacuum drying in the electrode process.

However, recently, according to concerns about the battery life issue that the deformation of a part of the jelly roll leads to its entire deformation, which can occur after improving the utilization efficiency of the inside space in the prismatic type (for the jelly roll, the can corner cannot be filled) and then, repeating charging/discharging thousands of times, the stacking construction method (for stack-type cells) is sometimes applied to large (especially, for xEV) prismatic batteries, instead of the winding construction method (for jelly rolls).

Figure 35 Summary of prismatic secondary battery assembly process



As for EV (EV) batteries, LGES and SK Innovation are producing pouch-types as their flagship, while Samsung SDI, CATL, and BYD are producing prismatic batteries as their main product. Recently, LGES has been supplying cylindrical batteries to Tesla for EVs. Panasonic manufactures cylindrical batteries for most of their EV batteries, supplying them to Tesla.

Table 21 Secondary Battery Types by Major Manufacturers

Manufacturer	Pouch-type	Cylindrical	Prismatic
LGES	○	○	○
SDI	○	○	○
SKI	○		
CATL			○
Panasonic		○	○
BYD			○

(Trend of New Technology for Battery Cell Manufacturing)

(New Technology for Electrode Manufacturing Process)[15]

The electrode process for LiBs is an essential process regardless of cell types, which is also an important process to determine most of the characteristics of a LiB cell. Therefore, development of the equipment and processes, equipped with new technology, is more urgently needed than other sectors; the following new technologies are being developed at present.

Table 22 New Technology for Electrode Manufacturing Process

Process	Current	New		Remarks
Overall	Wet electrode	Dry electrode	Extruder or New dry mixer	Dry electrode requires development/improvement of a variety of equipment, depending on the material formulation - including conductive agent, binder, etc. - and process concept.
			Laminator	
			Advanced Hot Roll Press for Dry electrode	
Mixing	Batch process	Continuous process		
	Pre-dispersion	One shot mixing (without pre-dispersion)		Active material, Conductive Additive, Binder, Functional Additives
	Carbon Black conductive agent	Updated dispersion method for CNT conductive agent (high BET and high aspect ratio material)		**Multi-wall CNT, Single-wall CNT**
Coating	Single layer coating	Multi layer (Die) coating*		*for Binder distribution optimization during drying(after coating)
		New drying system		Shortening the drying furnace and developing a new drying method
Pressing (Calendering)	-	Advanced Roll Press		Enhancing the film thickness accuracy and improving spring back

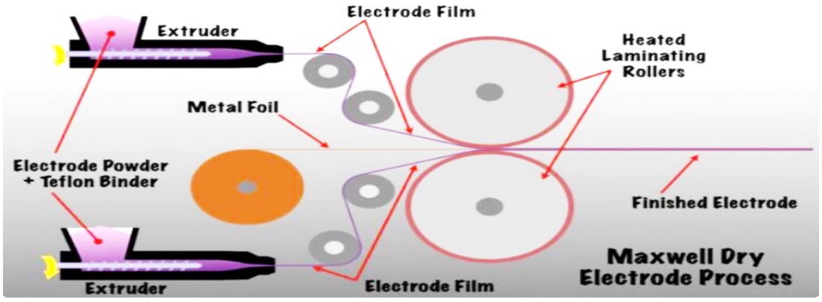
Dry Electrode technology for secondary batteries is a very powerful technology that can be applied not only to existing LiBs but also to next-generation solid-state batteries, and is being actively researched by LiB makers, such as Tesla, LG, Samsung, etc., as well as by various equipment companies, material companies, start-ups, research institutes, etc.

Advantages of dry electrode process are as follows:

- Easy to make thick electrodes and large areas
- Significantly reduced the material and process (drying) cost with solvent-free (No NMP) process
- No environmental problem thanks to No NMP, and various electrode formulations enabled
- Fundamentally removed moisture problems by blocking reaction between active materials and solvent
- Easy to manufacture thin film-type laminations

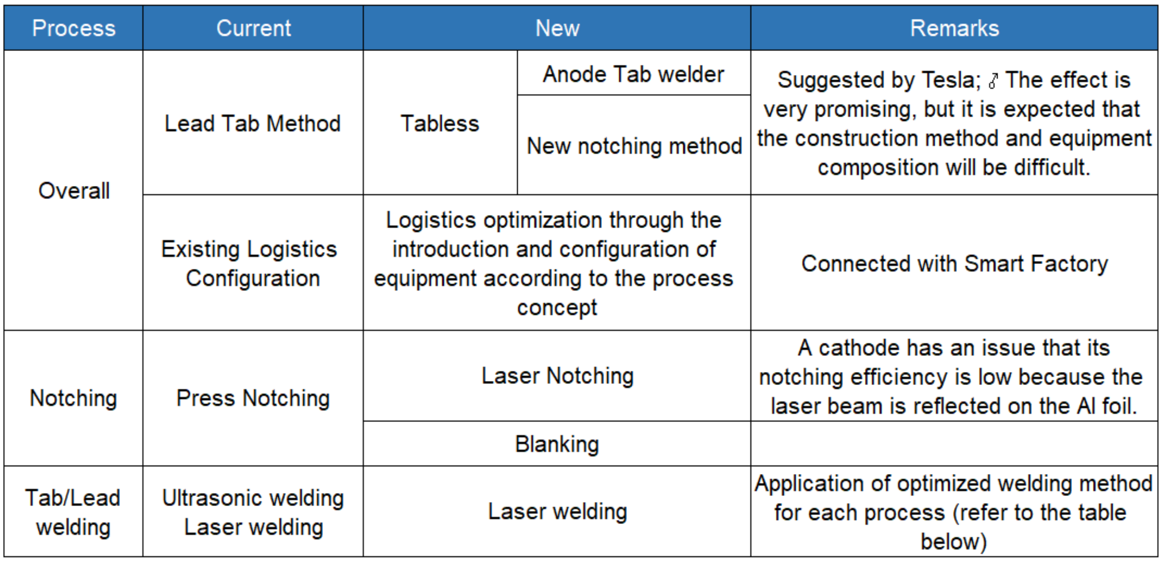
Figure 36 Maxwell Dry

Electrode Process(Tesla)



The secondary battery assembly process is very diverse depending on the cell type, process characteristics and history of each LiB company; therefore, it has a difference in the detailed configuration of the required process and equipment. However, as it has been commonly adopted, there are the following sectors requiring additional technology development.

Table 23 Trend of New Technology for Assembly Process



Process	Current	New		Remarks
Overall	Lead Tab Method	Tabless	Anode Tab welder	Suggested by Tesla; ♂ The effect is very promising, but it is expected that the construction method and equipment composition will be difficult.
			New notching method	
	Existing Logistics Configuration	Logistics optimization through the introduction and configuration of equipment according to the process concept		Connected with Smart Factory
Notching	Press Notching	Laser Notching		A cathode has an issue that its notching efficiency is low because the laser beam is reflected on the Al foil.
		Blanking		
Tab/Lead welding	Ultrasonic welding Laser welding	Laser welding		Application of optimized welding method for each process (refer to the table below)

The secondary battery formation process is mainly composed of logistics and electrical devices, and the inspection equipment to inspect battery properties and then, to determine whether it is good or defective is also one of major components.

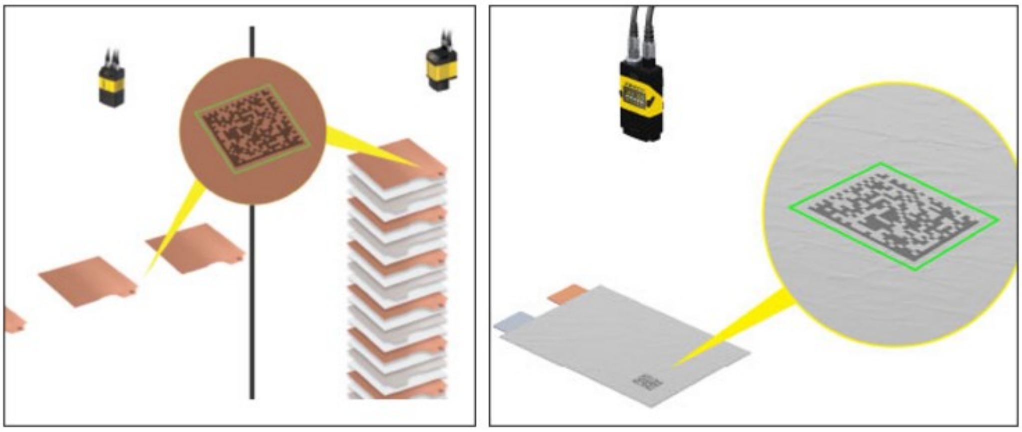
For Pouch-Type cells, it is a new trend to integrate the Assembly Process having the electrolyte injection and 1st pouch sealing with the Formation Process having the degassing and 2nd sealing. (A-Pro). Various technologies are being developed and applied to reduce the lead time of formation (14day → 8day) by utilizing high-temperature and pressurized charger/discharger, etc. and to improve the detection power of defects for characteristics, foreign matters, welding condition, and others. Improving the detectability/accuracy while reducing the tact time of inspection equipment and optimizing the logistics system for the Smart Factory is also an important technology development direction in the Formation Process.

Although the application of Vision System was limited in the early stages of secondary battery development due to higher costs, as stability of finished products is gradually emphasized, Vision System is being actively applied as a means of discharging the defects, occurring in each process, in a timely manner and of conducting real-time monitoring.

In particular, customers who purchase secondary batteries are not only purchasing batteries, but also monitoring production lines together, thus requiring quantitative measurement data through Vision system, Sensor, or the like.

Cell Tracking refers to the system that applies a unique number to raw materials beyond cell units in order to track what materials are used and under which conditions they are produced. For example, if a problem occurs with a finished product and the cause is determined to be the cathode, the process of sampling and inspecting half-finished/finished products produced at the same Lot of the cathode may be facilitated.

Figure 37 Example of Cell Barcoding



(Source : Cognex's website)

The system needs to store the parameters of all processes and the unique numbers of subsidiary materials; since the capacity is too large to store in the equipment, a dedicated PC must be installed and operated outside.

Recently, there is an increasing tendency of proactively introducing Digital Transformation (DX). Digital Transformation means that companies build and utilize Information and Communication Technology (ICT), such as Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), Big Data solutions, etc., as a platform to innovate the existing traditional manufacturing operation methods, services, etc. For the high-speed equipment in the current LiB manufacturing equipment field, under the judgment that productivity (yield and utilization rate) becomes lowered, they are focusing on advanced development, rather than speeding-up, in terms of maintenance and quality control.

Table 24 Digital Transformation (DX) Items

Item	Content
Logistics Automation	- Automation of electrode line logistics (AGV…)
In-line quality measurement	- Minimize QA (Quality Assurance) personnel by making In-line quality measurement
Quality auto-calibration	- Real-time calibration through quality monitoring: Need to expand sensor and vision installation sections
Equipment abnormality detection	- Real-time monitoring on the data, such as vision system noise, load cell pressure value, motor load factor, etc. - Utilize big data, derive and prevent BM causes
Quality setting automation	- Unify quality setting levels between equipment - Reduce new equipment setting time

The research and solution development are actively in progress on the Smart Factory having the increased automation and unmanned ratios through DX.

5. Recycling/Reuse[16]

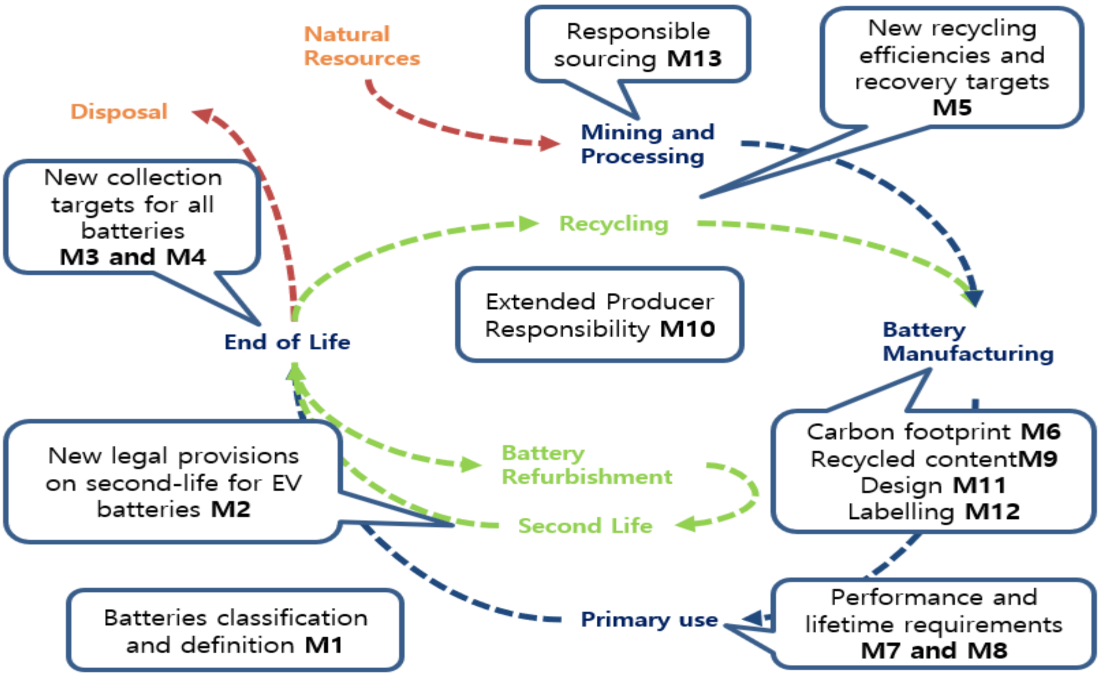
Similar to internal combustion engine vehicles, electric vehicles are decided to be scrapped after 8 to 12 years of use when the life of vehicles are expired. Based on its long history of use, internal combustion engine cars have a perfectly formed supply chain from sales of new cars to scrap of used cars. From the chain, valuable metals such as aluminum, copper, iron and platinum have been recovered and car parts have been reused without many difficulties. Unlike ICE cars, electric vehicles do not have parts/materials with a great value except used batteries.

Inside used batteries, there are toxic materials such as cobalt oxide, lithium, manganese, and nickel. If they are exposed to outside the battery, that could be hazardous with heavy metal pollution or formation of toxic gas. In addition, if used batteries are not properly treated, they may explode or catch fire in reaction to moisture. In case of explosion caused by fire, there may be a collateral damage from hazardous fumes. In order to reduce the carbon emission and energy use, battery recycling and reuse are regarded one of the important tasks to address in terms of social and economic perspectives.

To address these issues and promote the battery recycling/reuse, nations around the world have established their own battery management system by reforming or enacting related regulations. In Europe, a new regulation titled Battery Regulation was announced in December 2020, as they realized their previous battery guideline, Directive 2006, set for ICE vehicles did not have specific guidelines regarding recycled materials from wasted batteries and legal liability in wasted battery collection.

Europe's Battery Regulation was established to ensure the safety of batteries that are traded in the EU market and to create a sustainable ecosystem. The Battery Regulation sets 13 measures (M1~M13) over the entire life cycle of a battery and sets forth its target value.

Figure 38 Measures of Battery Regulation



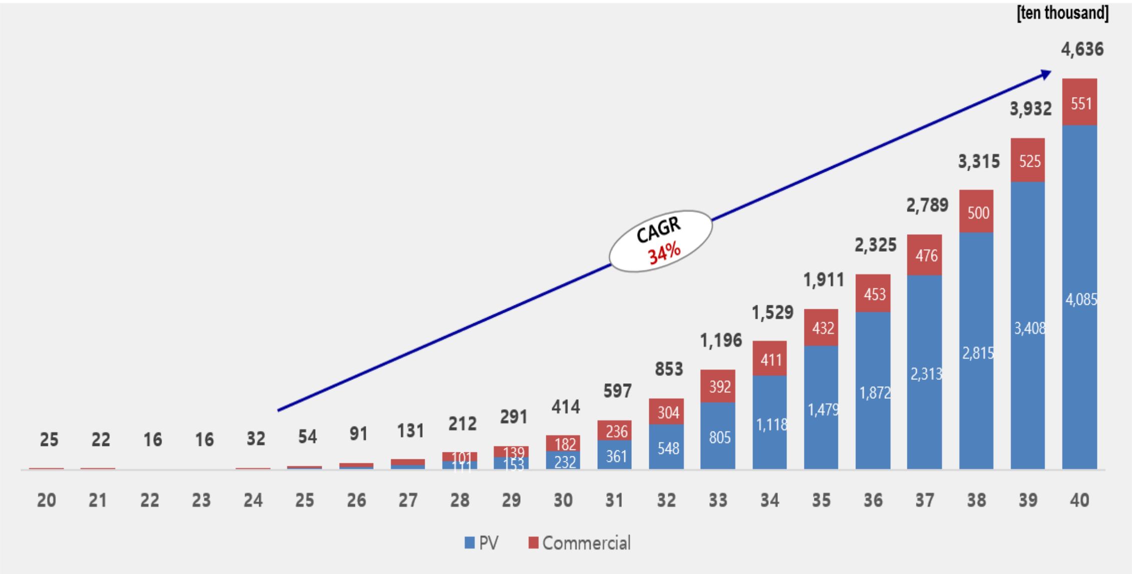
Among the measures in Battery Regulation, it is expected that measures about recovery materials, carbon intensity, recycled content, and due diligence for raw materials will mainly affect the industry.

In the US, Battery Recycling and Critical Minerals Act was submitted to the Senate to enact a legislation regarding wasted battery. The DoE (Department of Energy) seems to take a leading role in funding to create an ecosystem for battery recycling.

The most-recently enacted IRA (Inflation Reduction Act) stipulates critical minerals used for battery production. It also stipulates that when recycling, 10% of product production cost should be funded. In other words, in case of a new sales of an electric vehicle, only when critical minerals are supplied inside the US or from FTA partners with the US, a total of US$7,500 government subsidy is offered. Among the government subsidy, US$ 3,750(50%) is related to critical minerals. A certain portion of critical minerals necessary for battery manufacturing can be recovered from recycling, which leads to a reasonable expectation that the IRA may contribute a lot to the revitalization of recycling business.

China, which quickly introduced electric vehicles since 2016, is also quickly announcing regulations related to waste batteries. Regulations are being standardized according to value chain, but they have not been properly established yet.

Figure 39 Global Outlook of Volume of Scrap EVs(BEV/PHEV) Generated



* PV: all vehicles except for commercial vehicles

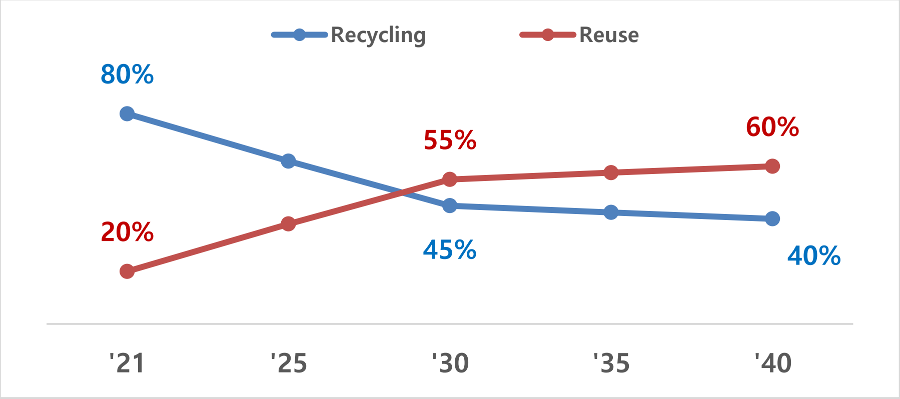
** Commercial: Commercial Truck/BUS

Most car makers have 8 to 10 years of warrantee for batteries used in their electric vehicles. The battery life is affected by the driving habit of drivers, temperature, the number of charging/discharging, etc. It is expected that passenger electric vehicles may have wasted batteries within 9 to 13 years of use, while commercial electric vehicles may have wasted batteries after 3 years of operation. Based on this assumption, the global volume of scrapped electric vehicles is forecasted as above in Figure 39.

In case of lead-acid battery already used inside ICE vehicles, it is mandatory to recover the battery, and the recovery rate in most countries is above 98%. As mentioned above, it has been decided to mandate the recovery of lithium-ion battery by establishing related regulations. The recovery rate of EV battery is expected to reach around 95% similar to that of lead-acid battery.

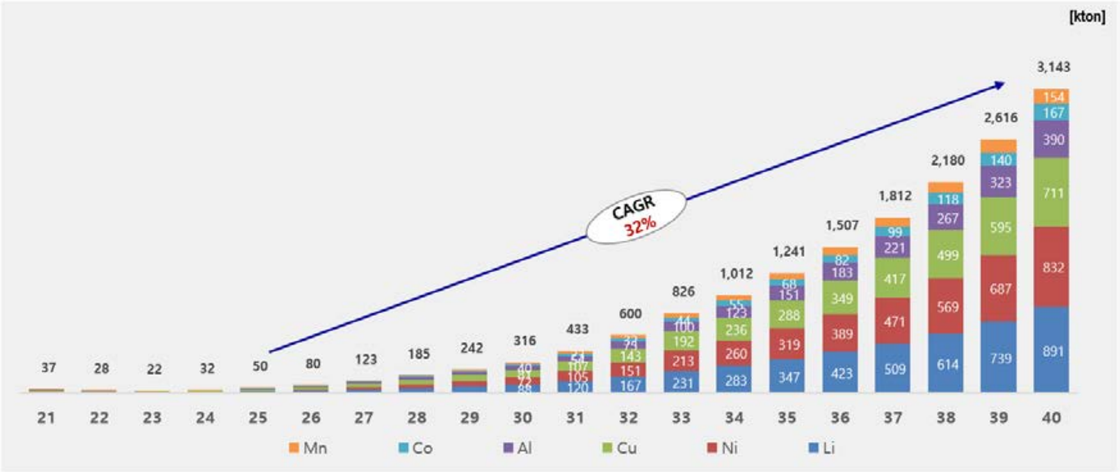
Batteries inside scrapped vehicles can be recycled or reused. The recycling/reuse ratio by years is suggested in Figure 40. It is expected that the ratio or reuse of wasted battery would increase due to the following factors: creation of added value when reused before recycling; and incorporation of social/environmental/legal requirements.

Figure 40 Outlook of ratio between recycling and reuse



Based on the recycling and reuse ratio and scrapped vehicles, the global recycling market can be forecasted as below in Figure 41.

Figure 41 Global Recycling Market Outlook



The reuse market, of which application has not been clearly decided yet, is expected to see significant changes in value depending on applications. In general, the industry expects that, based on a new cell, the value of reuse may reach approximately 50% of the cell value. Further studies are necessary to closely monitor and forecast the reuse market.

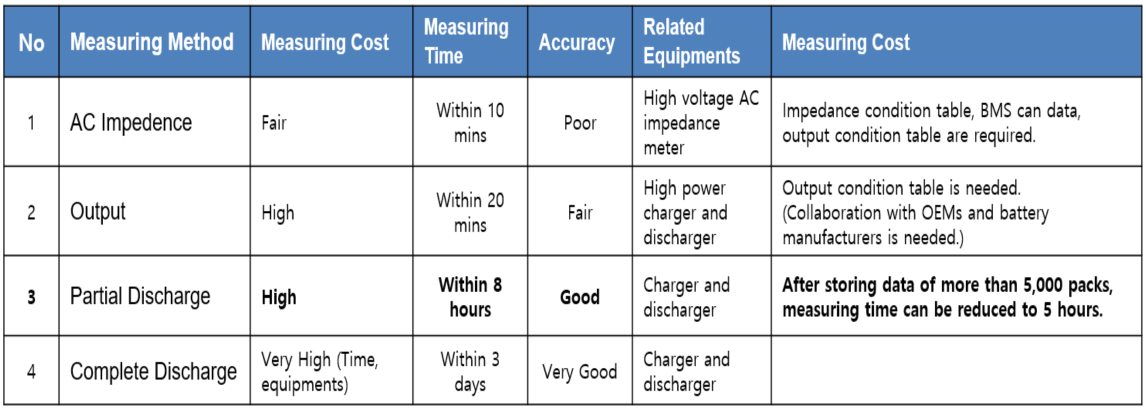
At the end of car operation, vehicles are scrapped, and in most countries, usually the registration of vehicle is cancelled according to a specific administrative procedure. At the end of procedure, vehicles are ended up in junk yards. The junk yards dismantle batteries from electric vehicles and discharge them before storing them for a certain period of time. To carry out these tasks, additional expenses may occur at the junk yards.

Dismantled batteries can go through the next processes once their ownership is transferred to professional collecting companies, reuse companies, or recyclers. If decided to be reused, wasted batteries are to go through temporary tests, pack testing and module evaluation to be used for a new purpose. Recycling companies carry out processes to recover valuable metals inside wasted batteries through pre-treatment and post-treatment processes.

(Measurement of Remaining Capacity of Wasted Battery)

There are a total of 4 methods to measure the remaining capacity of wasted batteries, but a method that can be utilized without the BMS information possessed by OEM is the partial discharge method. The table below shows advantages and shortcomings of each measurement method.

Table 25 Measuring Method for Remaining Capacity of Used Battery



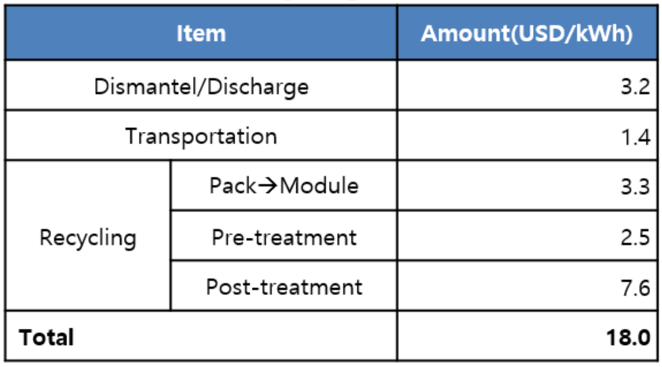
No	Measuring Method	Measuring Cost	Measuring Time	Accuracy	Related Equipments	Measuring Cost
1	AC Impedence	Fair	Within 10 mins	Poor	High voltage AC impedance meter	Impedance condition table, BMS can data, output condition table are required.
2	Output	High	Within 20 mins	Fair	High power charger and discharger	Output condition table is needed. (Collaboration with OEMs and battery manufacturers is needed.)
3	Partial Discharge	**High**	**Within 8 hours**	**Good**	Charger and discharger	**After storing data of more than 5,000 packs, measuring time can be reduced to 5 hours.**
4	Complete Discharge	Very High (Time, equipments)	Within 3 days	Very Good	Charger and discharger	

Partial discharge measurement has high accuracy, but it takes a long time and thus may incur a high cost for measurement. To lower the measurement cost, accumulation of large amount of data is necessary. For effective data accumulation, collaboration with OEMs and battery companies are expected to be required. In addition, equipment should be developed in accordance with required technology, which is another issue to be solved here.

Right after wasted battery is dismantled, recycling process should be carried out. In the process of recovering valuable metal, recycling companies should pay costs for basically required items. For instance, they should pay dismantling/ discharging/ logistics costs and also pay the owner of wasted battery (junk yard, professional wasted battery collectors, etc.) for expected battery value. Afterwards, there are additional expenses for pre-treatment and post-treatment.

Based on our interview, we came up with our estimate on recycling cost as shown in the below table.

Table 26 Calculation of Recycling Cost (based on 50kWh)



Item		Amount(USD/kWh)
Dismantel/Discharge		3.2
Transportation		1.4
Recycling	Pack→Module	3.3
	Pre-treatment	2.5
	Post-treatment	7.6
Total		**18.0**

*When calculating cost, each item is estimated based on interviews.

The amount shown in Table 26 does not include values expected by the owner of wasted battery recovered from scrapped electric vehicles. In case of ICE cars, when they are scrapped, the value of recovered metal (incl. used car parts) is high, including three-way catalytic valuable metals. Therefore, even after subtracting necessary expenses, a certain amount of money (US$30~50) can usually be refunded to the car owner.

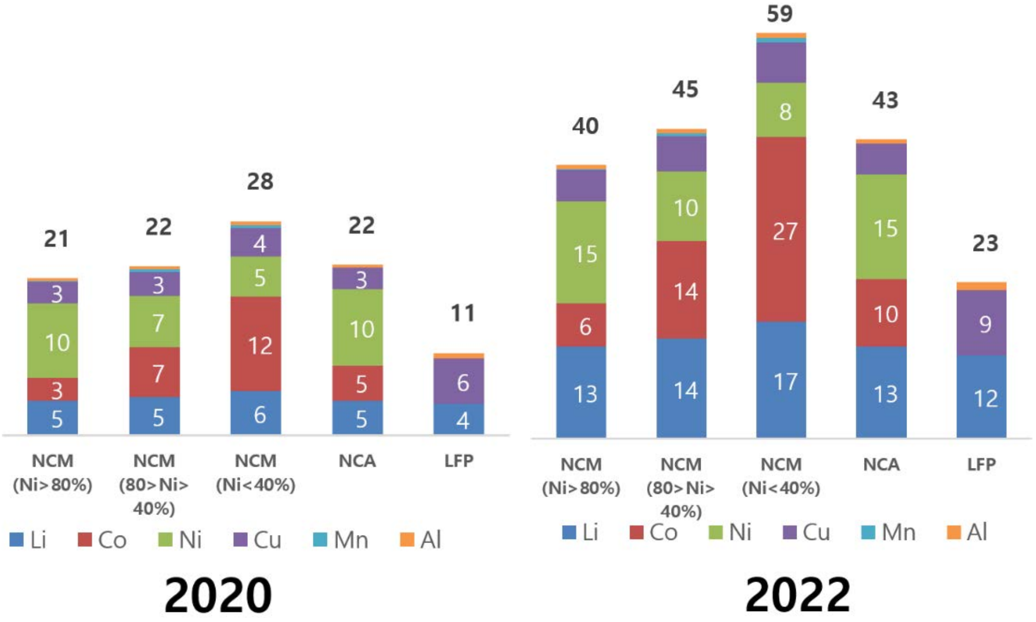
The recovery value of electric vehicles is not determined yet. In other words, we may need to have a special standard to determine the value expected by EV owners.

The total amount shown in Table 26, US$ 18, does not include such expected value. To minimize related expenses such as logistics expense, a wasted battery collection and recovery base may be built near locations where wasted battery are usually found. At the base, waste batteries can be fragmentized into black powder, which is easy to be shipped and stored, and then, they can be moved for post-process. This is a method called Spoke & Hub.

There is another method in consideration through which a recycling plant is built near the pre-treatment facility to optimize the shipping process.

The value of metal inside battery has increased almost twice for the past two years from 2020 to 2022 due to increases in the price of raw materials. In 2022, in case of NCM (80%> Ni wt% < 40%), the value of metal inside battery is US$ 45. If the purchase price is excluded, a profit of US$27 per kWh is created. In this regard, it can be concluded that the price of raw materials of today may has a significant impact on the economics of battery recycling.

Figure 42 Value of metals in batteries by year (USD/kWh))



As the battery recycling/reuse industry is an industry that is still actively growing and expanding, the related supply chain has been just formed and lots of issues lay ahead waiting to be solved.

1) Collection of Wasted Battery: The existing ICE cars are scrapped in junk yards, and electric vehicles are expected to go through a similar process through a supply chain that is similar to that of ICE cars. Wasted batteries dismantled in junkyards need to be discharged. Complete discharging of wasted batteries takes a long time, requiring special equipment of high cost. In addition, those dismantled and discharged batteries should be shipped for next processes. This logistical issue of shipping batteries from junkyards located across a nation should be also handled.

2) Measurement of Remaining Capacity of Wasted Battery: Wasted batteries can be utilized either by reuse or recycling. To determine their usage, the remaining capacity of wasted battery should be measured. Measuring the remaining capacity is highly likely to be performed at junkyards. In this regard, it is necessary to develop a measuring equipment that is simple and easy to use and at the same time at an affordable price.

3) Metal Recovery Rate: For recycling, technology to increase the recovery rate of various metals such as Ni, Co, Mn, etc. needs to be developed. While most of metals have technologies developed with a high recovery rate, lithium still does not have a properly established method to recover, which requires additional technology development.

4) Battery Categorization: Battery can be categorized into cylindrical, prismatic, and pouch types. Various battery chemistry is also applied, including NCM and LFP. In addition, the formation of battery pack and cell composition methods have been evolved to be in a more optimized form such as Cell To Pack to create a more harmonized composition with vehicles.

This, however, may act as an obstacle when it comes to battery reuse and recycling as those newly adopted and developed technologies make it difficult to figure out the exact components of battery.

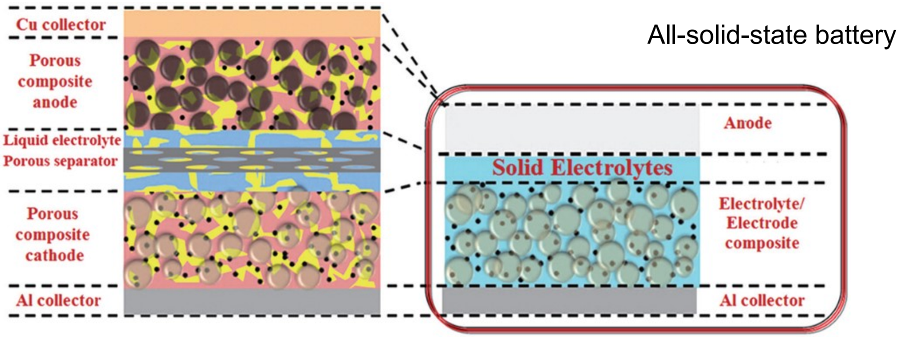
In Europe, there have been discussions going on regarding the establishment of standards and regulations to track and manage the history of battery in the form of battery passport and the like, but it still may require a long time before those standards and regulations are implemented.

6. All-Solid-State Battery[17]

Fire hazards, derived from inflammable organic electrolyte, may become serious issues when it comes to mid/large-size applications such as EVs. Liquid electrolyte currently used is decomposed outside the fusible voltage range and creates uneven membrane on the particle surface, making it challenging to enhance the energy density by applying high-voltage cathode such as high-Ni.

On the other hand, all-solid-state battery can fundamentally prevent issues with safety and electrolyte decomposition by replacing organic solvent electrolyte with solid one. As it does not require any separator inside, which thus increases the energy density per volume. Without electrolyte decomposition, the possibility of applying Li metal to anode can be increased.

Figure 43 Schematic Diagram of All-Solid-State Battery



Benefits can be expected from transforming the existing secondary battery with liquid electrolyte to all-solid-state battery are as follows: 1) increase in energy density; 2) possible application of new active materials; and 3) low activation energy. In addition, production processes such as separator winding, electrolyte injection, formation, and degassing can be eliminated.

However, as the development of related materials are not completed yet and thus, the manufacturing process has not been established, for now it is difficult to calculate the production cost of all-solid-state battery.

All-solid-state battery, called as a dream battery, has been subject to numerous R&D efforts made by many research institutes and companies. It is expected that all-solid-state battery would be launched to the market around 2026. Before 2026, different types of battery in various formats, such as a combination of secondary battery with liquid electrolyte and all-solid-state components, are expected to appear in the market.

The biggest difference between the existing battery with liquid electrolyte and all-solid-state battery is the difference of electrolyte state: liquid versus solid. That is, all-solid-state battery uses sold electrolyte to compose a battery instead of liquid one. Solid electrolyte can be largely categorized into inorganic and organic, and inorganic electrolyte can be subcategorized into sulfide and oxide.

1) Inorganic Solid Electrolyte

- Sulfide-based electrolyte: It has high ionic conductivity and relatively lower firing temperature. It is relatively ductile, making it possible to reduce the interfacial resistance only by cold pressing. It has shortcomings such as chemical instability to air; generation of harmful H_2S when contacted with moisture. Side reactions occur when contacted with oxide-based cathode active materials, making it necessary to have additional interface treatment.

- Oxide-based electrolyte: It is relatively stable against air and moisture. However, its firing temperature is above 1,000℃, causing problems such as lithium volatilization and phase transition. Grain boundary resistance is extremely high, resulting in lower ion conductivity than sulfide-based electrolyte.

2) Organic solid electrolyte

- Polymer-based Electrolyte: It is easy to process and highly ductile with low interfacial resistance between electrode/electrolyte. On the other hand, it has low mechanical material properties.

3) Hybrid Solid Electrolyte

- Oxide+Polymer: Materials (oxide/polymer) are mixed in a way to overcome weaknesses of each material to facilitate commercialization. Mechanical properties of polymer electrolyte are complemented, but the ion conductivity at room temperature is low.

If the idea of all-solid-state battery in which liquid electrolyte is changed to a solid one is specifically realized, the materials used in the existing supply chain and the process of making the battery may change. Since all-solid-state batteries are constantly being developed, it is expected that changes in materials and manufacturing processes will be inevitable. It has not been specified how different types of all-solid-state battery (oxide/sulfide/polymer) have influences on existing SCMs but given the current status of battery developers and their R&D efforts, changes in the below table are expected.

Table 27 Influences of All-Solid-State Batteries on Existing SCMs

Type	**Influences on Existing SCMs**		
	Manufacturing method	Chemistry	Remarks
Polymer All-solid-state battery	• Roll To Roll: Sheet-type solid electrolyte (Ionic Materials) • Both electrodes and electrolytes manufactured in sheet (Bollore)	• High-nickel is a main element amongst cathode materials • Trials to apply Li-Metal as anode materials	• If Li-metal is applied, anode current collector expected to be affected tremendously
Sulfide All-solid-state battery	• Roll to Roll: Separate environmental facilities to deal with toxic gases (sulfurized gases) (Solid Power)	• High-nickel is a main element amongst cathode materials • Graphite/Silicon/Li-Metal all applicable for anode	• Anode material Cu-foil reacts with sulfide (additional coating)
Oxide All-solid-state battery	• Large-area cell manufacturing is difficult with oxide alone • Hybrid-type to which previous methods are applied (Roll To Roll, by TDL)	• High-nickel is a main element amongst cathode materials • Graphite/Silicon/Li-Metal all applicable for anode	-

6.1 Sulfide-based Electrolyte

- Thio-LISICON-based

Normally, LISICON (Lithium Super Ionic CONductor)-based materials represented by $Li_{14}Zn(GeO_4)_4$ show the characteristic of high Li-ion conductivity. The Thio-LISICON-based has the structural formula of $Li_{4-x}M_{1-y}M'_yS_4$ (M = Si, Ge and M' = P, Al, Zn, Ga), and the Li_2S-GeS_2-P_2S_5 system was first developed by Kanno Group in 2001. The ion-conduction characteristic is determined by ion sizes, its polarizability, etc. In general, since the thio-LISICON-based has higher ionic conductivity than the existing LISICON-based materials by introducing S having a larger particle size, compared to O, and polarizability. The basic mechanism for ionic conductivity of Thio-LISICON-based solid electrolytes represents that the ionic conductivity is improved as cations of M and M' are replaced respectively. As Li ions are placed in the gaps within the LiS_4 tetrahedron and LiS_6 octahedron, the ions come to move through the conduction pathway generated along the ((LiS_6) octahedron structure.

- Binary sulfide-based

Li_2S-P_2S_5 binary system, often referred to as the LPS-based, has received a lot of attention because it has the high ionic conductivity of 0.1 mS/cm or more without elements like Si, Ge, Al, etc. Binary sulfide-based materials largely consist of five anion species: PS_3^-, $P_2S_6^{4-}$, PS_4^{3-}, $P_2S_7^{4-}$, and $P_2S_6^{2-}$. PS_4^{3-} is mainly observed in the material structure with Li_2S of 75mol% or more; $P_2S_7^{4-}$ is mostly observed in the material structure with Li_2S of 75mol% or less. In addition, $P_2S_6^{4-}$ is formed by the combination of two

PS3 units and P-P, which is observed as only one material structure in the binary sulfide-based. The remaining PS3- and P2S62- are observed in the composition of Li2S 60mol%.

- Argyrodite-based: Li6PS5Cl (LPSCl)

Reported by Deiseroth in 2008, it has the coordinated formula of Li_2S-P_2S_5-LiX and the *F-43m* structure. In the structure, *48h* (Li1) and *24g* (Li2) site play an important role in the diffusion of Li ions, which may provide 3D diffusion pathway.

- Others ($Li_7P_2S_8I$)

The Li ion transport pathway can be extended by introducing the halogen ion, I, into the Li3PS4 system. Through this, it can have the room-temperature ionic conductivity of 0.63mS/cm higher than β–Li3PS4. In addition, the material has a structure different from Li6PS5X, an electrolyte in which existing halogen ions are present. Particularly, the stability towards Li metals can be secured because the charge transfer resistance is lowered by introducing the halogen ion, I.

There are three main methods to produce sulfide-based solid electrolyte.

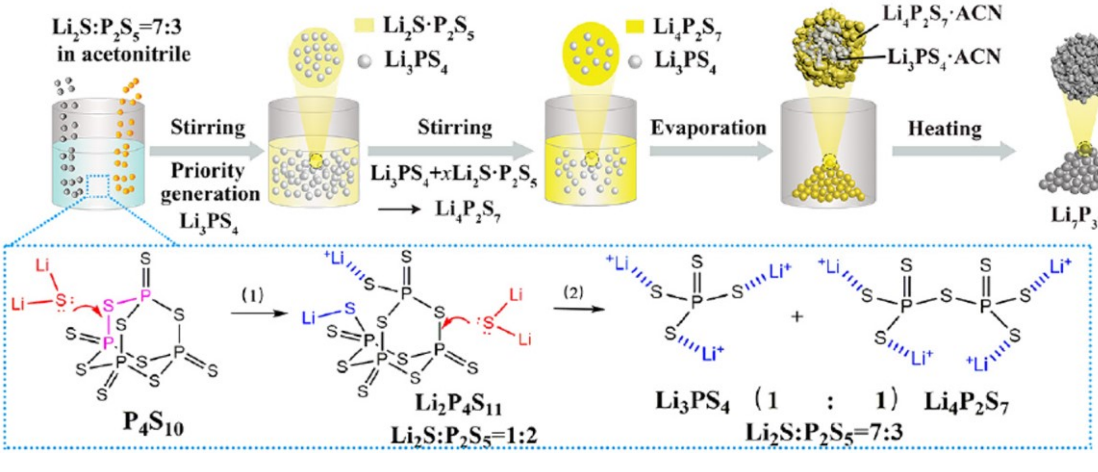
1) Solid-state synthesis: Most common method that is easy to synthesis and available for mass synthesis, but difficult to control the size of particles.

2) Liquid-phase synthesis: Using a solvent; easy to control the size of particles, but difficult to control the synthesis conditions and to synthesize in bulk.

3) Wet-chemical synthesis: Particles to be dissolved into a solvent before synthesis; easy to control the size of particles and available variations of application.

For example, liquid-phase synthesis is the method using a solvent; In organic solvents such as DME, ACN, and THF, Li_2S and P_2S_5 react and form Li_3PS_4-(organic solvent) precipitates in the early stage Thereafter, the solubility and the precipitate react to each other and form an intermediate phase; and finally, the final compound is formed from the mol reaction with Li_3PS_4.

Figure 44 Liquid-phase Synthesis



Core component among raw materials required for synthesis of sulfide-based electrolyte is Li2S, accounting for the largest proportion of the production cost (~$1,500/kg Normally, Li_2S can be synthesized by cold-pressing method, carbothermal reduction reaction, etc., but since various impurities such as Li_2O, LiOH, and Li_2CO_3 are formed during the synthesis process, it requires an additional refinement process.

To synthesize Li2S, various starting materials like Li metal, Li2CO3, LiOH, and Li2SO4 can be used, and depending on which starting material is used, a different synthesis method should be adopted. As a presentative example, Li2CO3 can be synthesized by reacting Li brine with soda ash (Na2CO3). Most of lithium compounds can be synthesized from Li2CO3. In addition, Li2SO4 can be synthesized by heat-treating spodumene (lithium ore) at a high temperature of 1100°C or higher, mixing it with hot H2SO4, and then reheat-treating it at 250˚C.

6.2 Oxide-based Electrolyte

- $Li_{1+x}Al_xGe_{2-x}(PO_4)_3$ (LAGP)

It has the structure that Ge is substituted for the transition metal site, whose electrochemical window is wider than that of LATP. Due to a chemical reaction in which Ge is reduced from 4+ to 3+ on the surface when contacted with Li metal for a long time, black by-products are generated. Since these by-products have the characteristics of the mixed ionic/electronic conductor, they can grow new by-products on the interface. when the reaction is accelerated, microcracks may occur because of the difference in volume between by-products and the electrolyte. Repetitive generation of the microcracks can increase resistance and even make solid electrolytes broken. Therefore, in order to suppress this reaction, studies have been under way to prevent direct contacts of the two by inserting a buffer layer between the electrolyte and Li metal.

-Perovskite-based

Perovskite-based electrolyte has the ABO_3 structure with the structural formular of $Li_{3x}La_{2/3-x}\square_{1/3-2x}TiO_3$ (0<x<0.167) (A=Li, La, □; B=Ti; □=vacancy). The electrolyte has a mixture of *Pm-3m* structure and *P4/mmm* structure and normally has a relatively high ion conductivity amongst other oxide-based electrolytes. In general, the *Pm-3m* structure has Li^+ and La^{3+} distributed in the A site disorderly. The *P4/mmm* structure has a high concentration of La^{3+} along the c-axis, and layers with many empty sites of Li^+ are alternately arranged in order. The ion conduction mechanism of LLTO is performed by the electrostatic attraction of each layered La^{3+} layer and the octahedral TiO_6 which exists between them. That is, due to the irregular arrangement of La ions at each La-rich and La-poor site in the $La_{2/3}TiO_3$ structure, the weak distortion in the structure occurs; because of these lattice defects, the path is formed through which lithium ions can move. Since LLTO has very high grain boundary resistance, there is a difference in the measured values of ionic conductivity on bulk and total samples.

-NASICON-based

NASICON(Na Super Ionic CONductor)-based materials generally have a structure formula of Na1+xZr2Si2xPxO12 (0≤x≤3). It was first reported by the Goodenough Group in 1976. In the NaZr2(PO4)3 structure, some of ions are replaced with Si and P ions and excess-Na ions are introduced. The structure is composed by corner-sharing of ZrO6, PO4, and SiO4, thus creating the 3-D diffusion pathway. A representative Li ionic conductive NASICON-based material can be expressed as Li1+xAlxM2-x(PO4)3 (0<x<2, M=Zr, Ti, Ge), generally known to have the R-3c structure. It is possible to increase the ionic conductivity by replacing a part of the transition metal inside the NASICON-based material with an element having a large ion radius. This is known to be caused by the reduction of activation energy. In fact, the activation energy reduces as the diffusion pathway is expanded due to distortions inside the lattice structure.

- Others: Li2.9PO3.3N0.46 (LiPON)

Developed in 1995, LiPON is an oxide-based electrolyte having the 3-D diffusion pathway. By sputtering Li3PO4 target in the N2 atmosphere, LiPON can be made in the form of film. Due to its very low ion conductivity of around 1.0 x 10-3 mS/cm, it can only be used in the form of thin film. As it takes the form of thin film, it has many advantages such as high energy density, high power, and fast charging, but the capacity gets very limited. If the thickness of film increases, the ion conductivity drops rapidly. However, thanks to the reducing features of N3- in the electrolyte structure, it is very stable even when in contact with Li metal.

There are two synthesizing methods for oxide-based electrolyte: solid-phase synthesis and liquid-phase synthesis.

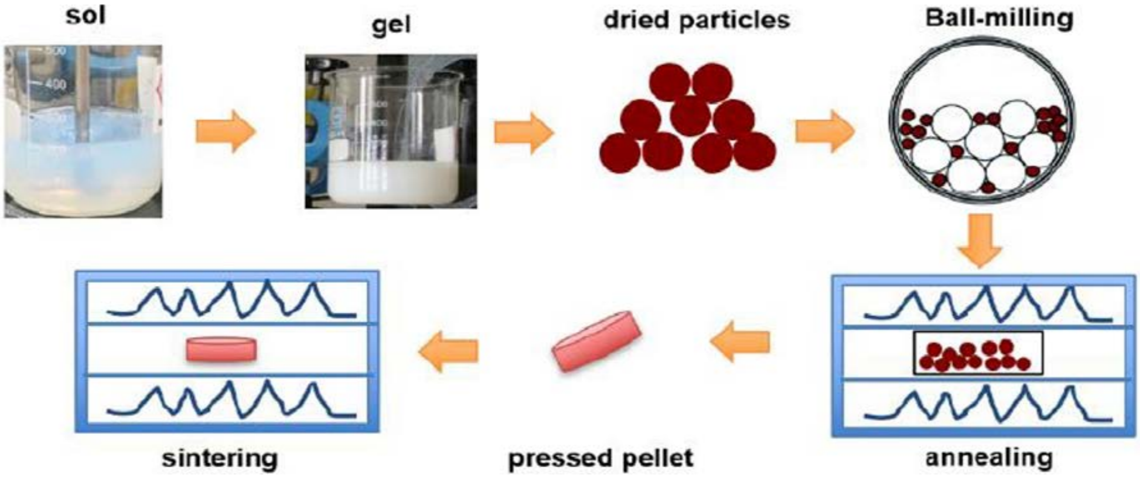
(Solid-phase Synthesis)

The typical method is to make pellets after mixing/crushing particles by ball-milling and then synthesize them through heat treatment at high temperature around 700-1200°C. Other than that, there are various solid-phase synthesizing methods, including the melt-quenching method synthesizing them after fusing the mixed particles at a high temperature of 1500°C or higher; the spark sintering method; the field assisted sintering method; and the microwave-assisted sintering method.

(Liquid-phase Synthesis)

Compared to the solid-phase synthesis, firing temperature is lower and controlling particles sizes and shapes is easier. One of the commonly used liquid-phase synthesis methods is a sol-gel method. With this method, an electrolyte can be synthesized within relatively a short period of time and with high purity. In addition, as the method allows synthesis in bulk, the sol-gel method can synthesize 1kg of LATP with 95% purity. Depending on types of raw material or solvent, the heat treatment conditions, etc., the ion conductivity or lattice structure of final synthesized electrolyte may vary.

Figure 45 Schematic Diagram of Liquid-Phase Synthesis for Oxide-based Electrolyte



6.3 Polymer-Based Electrolyte

- PEO-based Electrolyte

PEO(poly(ethylene oxide)) has a repetitive unit and is composed of –CH2CH2O-. The polymer-based electrolyte, using PEO and lithium salt, was first developed by Wright, et al., in 1973. Oxygen atoms indicating polarity allows the coordination bonds with alkali metal ions to be easily formed. This is because the electron-donating feature of oxygen atoms is greater than that of other polar atoms (N, S, etc.) with ion-coordinating ability. For this reason, alkali metal cation and oxygen in ether coordinate, creating a complex and possibly causing lithium salt to be dissolved. The ionic conduction of PEO mostly occurs in the amorphous area, and the ion conduction occurs through the hopping mechanism. The higher crystallinity of PEO gets, the lower ion conductivity is. In this regard, by introducing additives to suppress the crystallinity, the ion conductivity may enhance. In addition, depending on types of lithium salt, the ion conductivity varies.

- Polymer/Ceramic composite (Hybrid electrolyte)

PEO has an excellent ability to dissociate lithium salt, so in early days most of studies focused on the characteristics of PEO itself. However, due to its high crystallinity, the polymer chain has very low flexibility, thus leading to very low ion conductivity of 10-4-10-2 mS/cm at room temperature. Therefore, to enhance the conductivity characteristic, studies on mixing PEO, other polymer, and inorganic materials have started. On the other hand, since the inorganic solid electrolyte forms a solid-solid interface with the active material, high interface resistance occurs. Given this interface resistance issue, studies in the field have steered to introduce the solid electrolyte into polymer electrolyte as filler to create a hybrid electrolyte in the end. In the early stages, the solid electrolyte filler can be used to lower the crystallinity of polymer and then encourages the ionic conductivity to increase. Its electro-chemical performance varies depending on the content of polymer and solid electrolyte.

Blending method for PEO-based electrolyte is as follows: Raw materials are put into organic solvents such as CAN which can dissociate lithium salt and copolymer and then stirred it till slurries with viscosity are formed. Afterwards, on the supporter like Teflon, slurries are casted and then dried at a constant temperature in the vacuum atmosphere to make the electrolyte film of uniform thickness.

Blending method for polymer/ceramic composite is as follows: raw materials are put into the organic solvent and dissolved, and then the inorganic solid electrolyte of a certain ratio is added and stirred till slurries are formed. Thereafter, the slurries are casted on the supporter and dried at 60°C in the vacuum atmosphere to make an electrolyte film of a uniform thickness in the end.

(Problems of All-Solid-State Battery & R&D Trend)

All-solid-state battery has various issues incurred by high interfacial resistance, electrolyte thickness, segregation, and void formation due to the formation of solid-solid interface. These issues need to be overcome before actual commercialization. There have been various R&D efforts made to overcome these issues.

Issues rise when developing all-solid-state battery with sulfide, oxide, polymer or other electrolytes. The table below summarizes attempts made to address those issues and their estimated outcomes.

Table 28 Drawbacks of Electrolyte by Type (Large-sized battery)

Electrolyte	Technical Issues	Solutions (Estimated)*	Solution Effectiveness (Interviewed)	Target Company	Remarks
Sulfide	1. Formation of resistance layer between cathode and electrolyte layer	Cathode material surface coating	Effective	Toyota	Zero possibility in mass production when pressurized ※ Solid Power insisting most of issues to be solved
	2. Reactive to moisture	Production in dry room condition; separate device to deal with issues in vehicles	Effective	Solid Power	
		Developing materials less reactive to moisture	Ineffective	Mitui	
	3.Thickness of electrolyte layer	Wet painting process introduced	Ineffective	Toyota	
	4. Electrolyte segregation	Homogenous mixing	Ineffective	Toyota	
	5. Electrolyte layer void	Pressurizing	Effective	Hitachi Zosen	
	6. Impossible serial production	Solvent and binder developed and made into slurry	Ineffective	Toyota	
	7.Very poor range of reproducibility		Ineffective	Domestic A company	
Oxide	Brittle materials hard to make large-area battery	Ceramic + Polymer	Ineffective		Nothing verified other than polymer/ceramic hybrid
		Ceramic + small liquid electrolyte	Ineffective		
Polymer	1. Operation temperature range	Heating equipment attached	Effective	Bollere	Low energy density
	2. Voltage	LFP cathode material used	Effective	Bollere	
	3. Low ion conductivity	New polymer development (PLA/PEO mixing)	Ineffective	Ionic material	
Nonflammable liquid electrolyte	1. Low ion conductivity	New material development	Ineffective	SES	Not verified
	2. Energy density (using Li-metal)	Thin Li-metal production (~10 micron)	Ineffective	SES	
Others (Semi-solid electrolyte)	Mass production		Verification required	24M	Cost issues

- In case of oxide electrolyte, sintering at high temperature is required in the process of manufacturing. The material itself is brittle, known to be difficult to make large-area battery cell with it. As a solution to that, the semiconductor manufacturing process is used to produce small-size battery cell by companies like Almac, Applied Material, STMicroelectronics, and TDK. Applications include replacing small condensers previously used for electronics parts. Later, it is expected to take up a certain portion of market, supported by continuous investment and enhancement efforts. When it comes to the production of large-area battery cell using oxide materials, there has been an attempt to produce a battery by mixing with a certain amount of liquid electrolyte or viscous polymer electrolyte. (Using the Roll-To-Roll method previously used for the production of LIBs).

- Sulfide electrolyte in the form of powder is known to be difficult to make a thin layer of electrolyte only with the powder itself. Even if a layer with consistent thickness is successfully made, the electrolyte layer inevitably contains voids due to the characteristics of powder. In addition, as mentioned earlier, sulfide reacts with moisture and creates sulfide gas, making it necessary to come up with proper countermeasures. To address this issue, there are many attempts with various solutions to make sulfide in the form of slurry. For example, a binder can be used as it does not react with sulfide and can be used inside battery cell without disrupting the material characteristics of battery. It seems there have been active research going on in this field of study. Once such binder is developed, the sulfide electrolyte can be made in slurry and via the Roll-To-Roll method, battery can be manufactured. The development of binder seems to be the key to the issues in manufacturing the sulfide all-solid-state battery. Meanwhile, there are also lots of efforts made to develop a material less reactive to moisture and highly ionic conductive. Companies in Japan are key players in this area, including Mitui, Idemitsu Kosan and Sumitomo Metal Mining. Often, R&D is conducted by adding functional materials to the previously developed sulfide materials or by taking advantages of the characteristics of oxide materials.
- It has been reported that polymer electrolyte does not have any serious manufacturing issue, but the operation temperature is over 60 Celsius degrees. There have been many studies going on to lower the operation temperature, while Bollere claimed that it succeeded in dropping the operating temperature to the room temperature.

6.4 Various Types of Batteries; Hybrid/Semi Solid)

Recently, there are various type of batteries in development that can take advantages of all-solid-state batteries. There are mostly made by minimizing the use of liquid electrolyte used for the existing LIBs or by apply Li-metal as anode instead of graphite. Many solid-state makers, particularly those using oxide as electrolyte (e.g., Prologium, QuantumScape, etc.), are assumed to add a very small amount of liquid electrolyte as additives. Representative companies using the features of all-solid state are 24M in Japan and SES in the US.

24M, for instance, claimed that the production cost can be reduced to 25% by using liquid electrolyte as solvent and making cathode and anode slurry into a dough. This removes the processes of solvent drying, recovery, and liquid electrolyte injection, as well as does not require separators and current collector anymore, thus leading to cost reduction. In addition, binder-free slurry is created and made in a form of thick electrode, making it possible to design high-energy-density cells and saving time and money for manufacturing. On the other hand, the thicker cathode and anode materials get, the less heat is released from the inside of battery cell to the outside. In this regard, concerns about fast charging and operating temperature still exist in the industry.

Freyr, a Norwegian battery maker, recently signed a license agreement with 24M and suggested that it would build its own battery plant in Europe and the US. (Total production scale to be 0.2 GWh / Starting from 2022, investment to be made to achieve 83 GWh by 2028).

VM, which also announced of technical cooperation with 24M, has not clarified whether the production line to be based on the semi-solid technology. Recently, it seems to be more specified that the production facility based on the technology has been under its full-scale construction. Thus, it is expected that the market penetration by VM may extend its range and depth based on the technology.

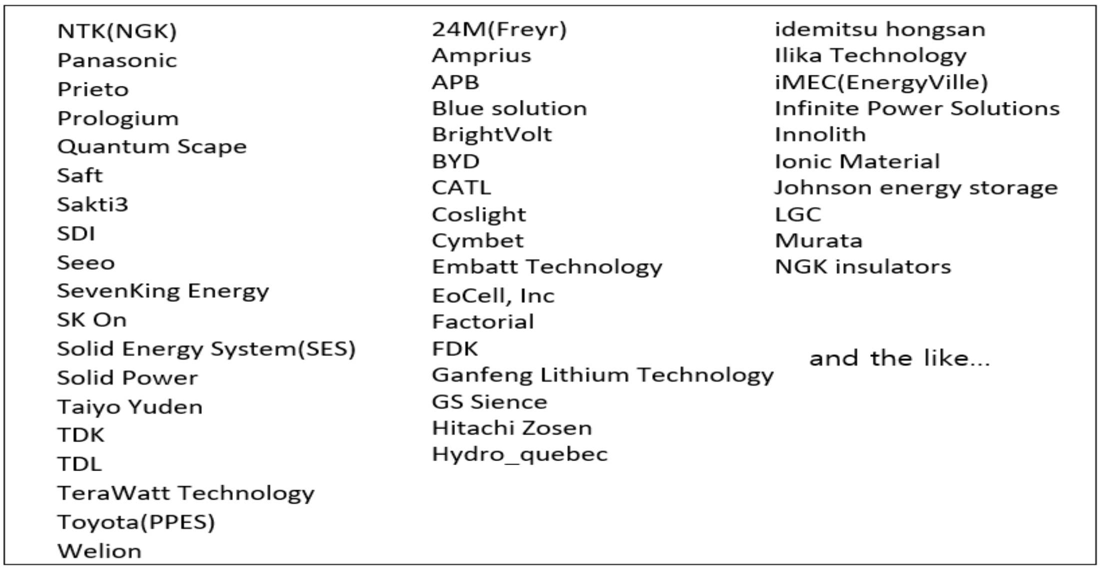
Another company trying to take advantages of all-solid-state batteries is a US startup, SES. Batteries made by SES are hybrid batteries made by filling the electrolyte entirely with solid materials but mixing liquid approximately at around 10% of the total. SES claimed that the battery can be fast charged up to 90% within 12 minutes. With Li-metal used as anode, it is also called as Li-metal battery. It uses around 10 um, ultra-thin film Li-metal foil. By coating the surface of Li-metal with polymer and organic materials, the growth of dendrite can be suppressed, claimed to be effective in stabilizing the characteristics of battery life. SES established a plant in Shanghai, China, which started operation in 2019. Recently, SES unveiled a new pouch-type cell, ‘Apollo,’ to the Korean market. According to SES, the cell, only weighing 0.982 kg, has 107 Ah of the capacity and 417 Wh/kg.

The core technology of SES is a super-thin Li-metal foil and liquid electrolyte with excellent temperature characteristics and high ionic conductivity. The production line unveiled by SES was for Li-metal foil with approximately 30 cm width made in rolls. To prevent the growth of dendrites, the foil roll is coated with polymer which is mentioned in the US patent (US10347004) as having two polymer layers. Li-metal is known to be very difficult to be elongated thinly. The Li-metal foil is currently made by a Chinese company whose details have not been exposed to the market yet.

(All-Solid-State Battery Market Outlook)

A total of 54 companies which plan to develop and mass-produce all-solid-state batteries were surveyed; 18 in North America; 7 in Europe; 7 in Japan; 10 in China; and 7 in Korea by region. In Europe and North America, oxide- and polymer-types take a strong hold. In Japan, oxide and in Korea, sulfide are regarded main materials for all-solid-state battery.

Table 29 List of surveyed companies (54 companies)



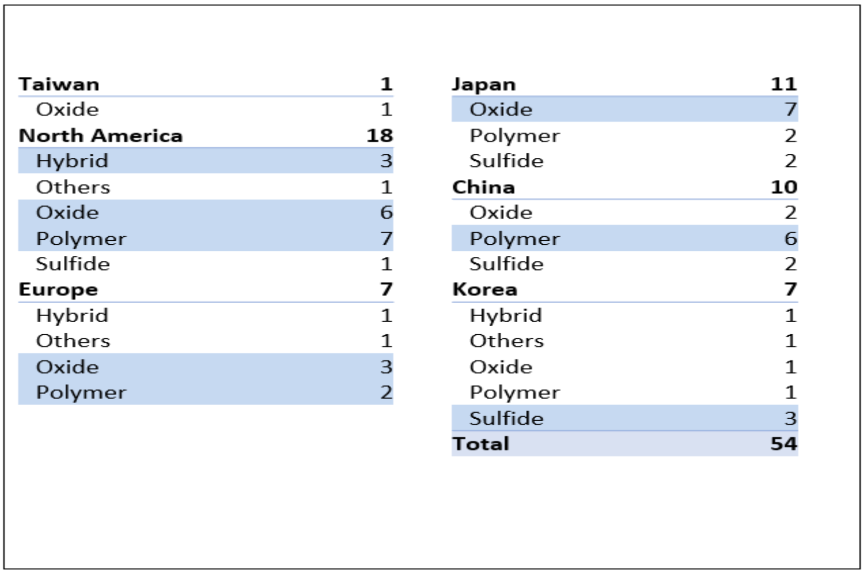
NTK(NGK)
Panasonic
Prieto
Prologium
Quantum Scape
Saft
Sakti3
SDI
Seeo
SevenKing Energy
SK On
Solid Energy System(SES)
Solid Power
Taiyo Yuden
TDK
TDL
TeraWatt Technology
Toyota(PPES)
Welion

24M(Freyr)
Amprius
APB
Blue solution
BrightVolt
BYD
CATL
Coslight
Cymbet
Embatt Technology
EoCell, Inc
Factorial
FDK
Ganfeng Lithium Technology
GS Sience
Hitachi Zosen
Hydro_quebec

idemitsu hongsan
Ilika Technology
iMEC(EnergyVille)
Infinite Power Solutions
Innolith
Ionic Material
Johnson energy storage
LGC
Murata
NGK insulators

and the like...

Table 30 No. of Companies by Region/ASB type

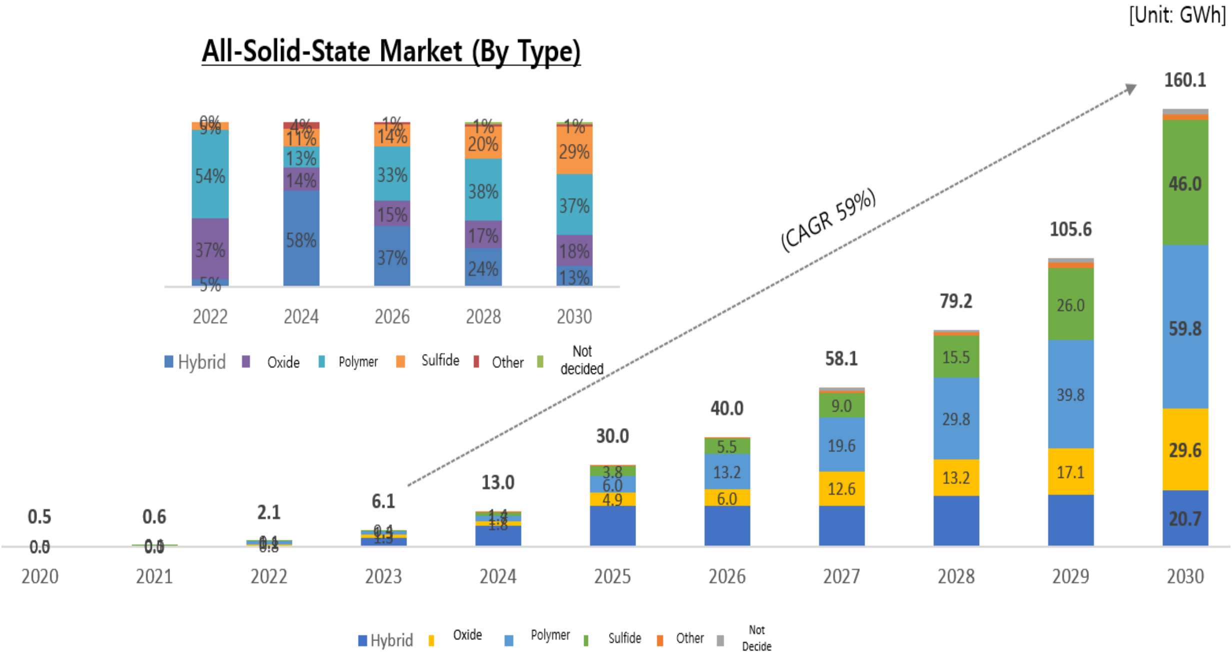


Taiwan	**1**
Oxide	1
North America	**18**
Hybrid	3
Others	1
Oxide	6
Polymer	7
Sulfide	1
Europe	**7**
Hybrid	1
Others	1
Oxide	3
Polymer	2
Japan	**11**
Oxide	7
Polymer	2
Sulfide	2
China	**10**
Oxide	2
Polymer	6
Sulfide	2
Korea	**7**
Hybrid	1
Others	1
Oxide	1
Polymer	1
Sulfide	3
Total	**54**

By using the semiconductor process, all-solid-state batteries are expected to be first commercialized for small IT products. Starting in 2022, all-solid-state batteries utilizing oxides/polymers are projected to be released in the market. This means that it is more likely to be applied to ESS earlier than automobiles. Blue Solution applied the polymer-type all-solid-state battery developed themselves to the pilot project (xEV/ESS) in 2020 and is expected to expand the business to a market scale after 2022. In addition, types of solid electrolyte battery with a certain amount of liquid such as Hybrid or Semi-solid are expected to be used.

At the nascent stage of all-solid-state battery market, polymer type and solid electrolyte, such as hybrid, battery are expected to take the lead in the market as the former takes advantages of the existing mass production facilities, and the latter has greater accessibility in terms of technology. In 2030, oxide/polymer/sulfide/Hybrid types are expected to compete with each other, pushing the boundary of the entire market.

Figure 46 All-Solid-State Market Outlook by Type



7. EV Charger & Charging Infrastructure

There are three ways to supply electric power to electric vehicles: direct (conductive) charging, in direct (inductive) charging, and battery swapping. Among them, most of chargers commonly used by drivers adopt the direct charging method.

- Direct Charging Method

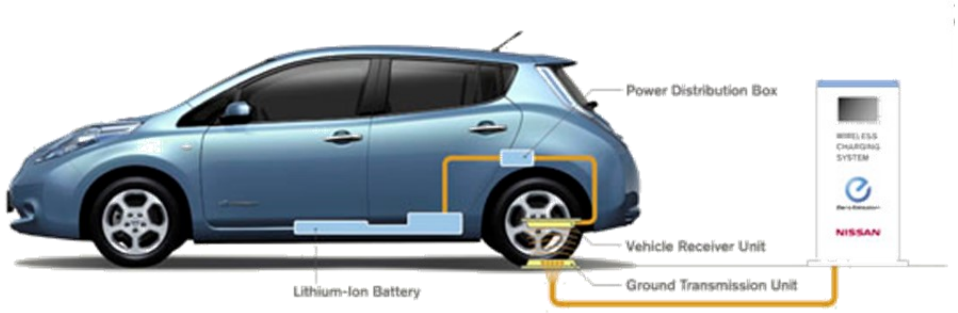
Destination Charging) Through cables connected to a charger, 220-volt AC is supplied to electric vehicles. 3kW-onboard-charger equipped to electric vehicles transfers 220-volt AC to DC and then the battery is charged. Depending on the capacity of battery, it takes 8 to 10 hours for charging. Chargers with approximately the power capacity of 6~7kW are often installed.

Super Charging) A charger exchanges control signals with vehicles, supply 100~450-volt DC to charge the batter. It is high-voltage and high-capacity charging, thus reducing the charging time.

- Indirect Charging Method

When vehicles temporarily stop at parking lots and personal garages, or for traffic lights, or while vehicles are driving, the wireless charging system enables electric vehicles to be charged. Usually, the wireless charging system offers benefits such as durability, user-friendliness, and esthetic design. However, it has not been widely used and commercialized yet due to the following shortcomings: electromagnetic compatibility (EMC), limitation in power transmission, large-scale and high-cost infrastructure, limited charging range, and low efficiency.

Figure 47 Schematic Image of Wireless Charging by Nissan



(Source: Springer, MoneyS,, Nissan-global.com)

Indirect charging can be categorized into three different methods: magnetic resonance method, magnetic induction method, and electromagnetic wave method.

Magnetic resonance method enables charging without coils in contact. Coils in the transmission unit create the magnetic field oscillating with resonant frequency. The energy is concentrated and transferred to coils in the receiving unit using the same resonant frequency. Charging coils and electric vehicle batteries should be located within the range of approximately 10 meter (max) and the same frequency should be used to enable charging.

Magnetic induction method is currently used for wireless charging of smart phones. The method utilizes the phenomenon of magnetic induction between transmitting-receiving coils. However, the allowed distance for wireless charging is short, thus requiring transmitting-receiving medium to be closely contacted.

The electromagnetic wave method sends remote electricity to chargers located hundreds of meters away by using frequency in hundreds of MHz to even GHz band and sensors then collect those electric energy sent remotely. The transmission range is very broad – around several hundred meters to several kilometers

– and high output can be applied, but since the distance is quite long, the transmission efficiency is low (around 10~50%). It also has other issues such as electrons.

Lastly, the battery swapping method allows charging station operators to utilize the electricity during time slots when the load rate it low to charge spare batteries. Drivers drop by charging stations to change their electric vehicle batteries with new ones semiautomatically. As drivers are provided with already-fully-charged batteries at the station, they do not have to wait for their batteries to be charged. In addition, battery ownership is held by the station operators, helping lower the price of electric vehicles. On the other hand, there are also issues to tackle, too: battery compatibility issues and negative response from electric vehicle users regarding battery sharing.

Figure 48 Image of Battery Change Done by Driver

(Source: Korea Environment Corporation, News 18)

The battery swapping can be categorized into direct and semiautomatic ways. The direct swapping method allows battery users to change batteries at battery swapping stations located in urban areas. This method is mostly used for small-sized mobility such as two-wheeled vehicles. Countries like India have been considering the introduction of direct battery swapping.

Semiautomatic swapping refers to battery swapping done by automatic system at battery swapping stations where electric vehicles enter. Drivers simply drop by the swapping station and shortly park their cars for battery swapping, but the initial construction cost for stations is high. Currently, mainly in the US and China, semiautomatic swapping has been tested with shared vehicles and commercial vehicles.

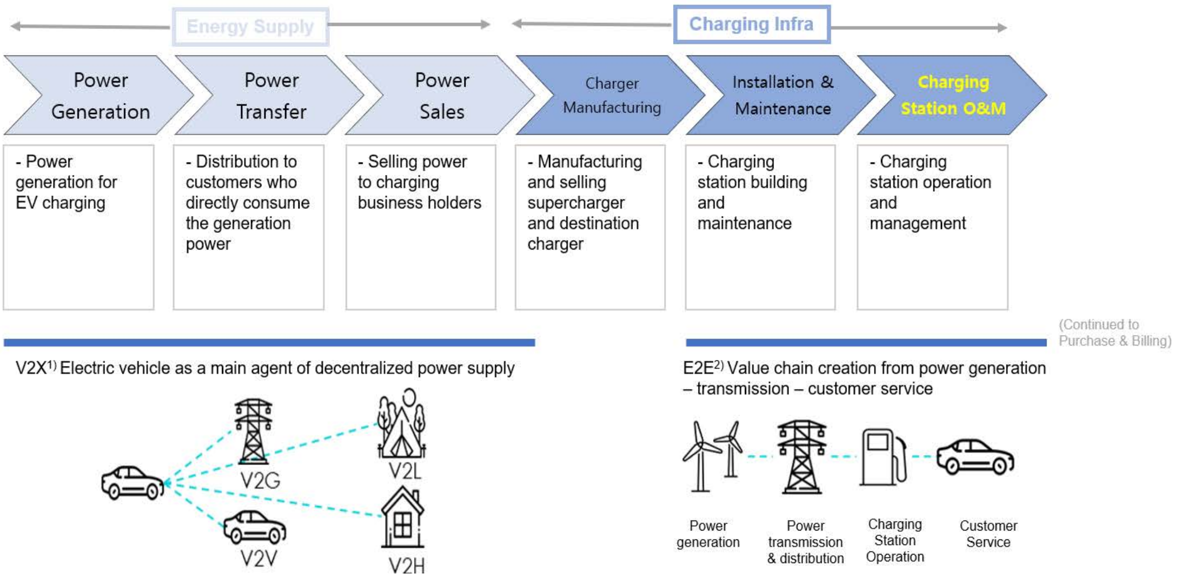
There have been numerous research and development going on to increase the charging rate, but a lot of questions regarding its effectiveness have risen, too. For now, the current format of charger is expected to last for the time being. Table 31 below shows the benefits and shortcomings of charging methods.

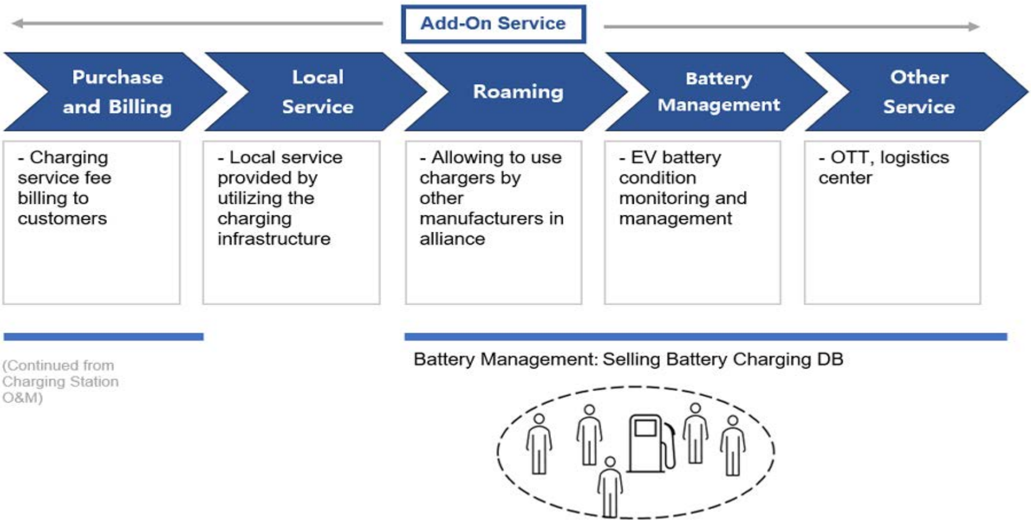
Table 31 Trend in Development of Charging Method

	Features	Benefit/Shortcoming
Battery Swapping	Like chaging used batteries of mobile phones, electric vehicle batteries are swapped with fully-charged batteries.	Swapping only takes one minute.
	Batteries can be leased, which lowers the price of electric vehicles.	Initial investment for swapping station and devices is high. (EUR 1.45 mil. / 1 set)
	China trying to apply battery swapping to commercial vehicles, while Korea has been testing in a small scale.	Standardization of battery (Unification of battery design by OEMs)
Direct Charging	Max output can be found in Tesla (250kWh) and Combo 2 (350kWh), supporting 400V and 800V respectively.	The charging rate may be increased, but the charger parts and battery technology are not advanced enough.
	* Due to insulation issues, over 1,000V cannot be applied.	
	Standardization of charging with over 350 kWh has not been discussed.	
Wireless Charging	Wireless charging	Intial investment is too high.
		Public awareness about harmlessness should be fostered.

Battery charging station operators have opportunities in the early and later stages of the value chain such as energy supply and add-on service. There are new business models in development now including V2X and E2E. Figure 49 below shows a model of new business currently in development.

Figure 49 Battery Charging Value Chain and Business Model





Add-On Service

Purchase and Billing	Local Service	Roaming	Battery Management	Other Service
- Charging service fee billing to customers	- Local service provided by utilizing the charging infrastructure	- Allowing to use chargers by other manufacturers in alliance	- EV battery condition monitoring and management	- OTT, logistics center

(Continued from Charging Station O&M)

Battery Management: Selling Battery Charging DB

1) V2X: Vehicle to X

2) End to end

8. Opportunities for Netherlands in Battery Industry with Korean Battery Players

8.1 Players and their market potential with strong points

In an effort to convert to climate-neutral economic system in the long term, Europe has been trying to establish a value chain for battery. The Netherlands, an EU member country, announced <Voortgang strategische aanpakbatterijen> as a strategy to establish its own battery chain in December 2021. This report includes some of the updates in battery projects and strategies made since November 27, 2022. The ministers of Infrastructuur en Waterstaat, Buitenlandse Handel en Ontwikkelingssamenwerking, and Economische Zaken en Klimaat have announced the related strategies, while 9 different government organizations other than those ministries have been also striving promoting the battery industry. The Netherlands has its focus on the battery reuse and recycling sectors to build the energy circulation system. According to a report provided by the Battery Competence Center in December 2022, there are a total of 48 companies in the battery system sector (6 small-sized companies, 25 medium-sized companies, and 17 corporates); 15 companies in the second-use and recycling sector (5 remanufacturing and second-use companies, 6 dismantling and material recovery companies, and 4 logistics and safety companies); and 18 companies in the battery material related sector (3 R&D companies, 5 startups, and 10 battery process and equipment companies).

This report suggests the requirements for the Dutch companies to cooperate with players in the Korean battery market and possible business items that they may find potential opportunities in cooperation. To come up with the suggestion, the report is based on research and analysis of conditions and strong/weak points that the Netherlands has in the battery system, second-use and recycling, and battery material sectors.

(1) Battery Systems (VDL, DAF, Damen, Eleo, EST-Floattech, etc.)

Battery system refers to a complete energy storage system which includes battery pack and module consisting of battery cells and is added with cooling system, sensors, and other components. The main players in battery pack production for electric vehicles have been battery makers or battery-related companies in the past, but the focus has been shifted to OEMs. In this regard, battery makers are expected to concentrate on cells and modules. The battery system sector is inevitable to have a very close relation with companies or regions where final products are made. The battery system sector in the Netherlands seems to focus on items the country wants to further develop or expand, and those are for special purposes such as vessels and tractors. In terms of battery cell which requires different components and battery system depending on environment changes, it is assumed that the Korean companies may have interest in those items for special purposes. On the other hand, the Korean companies may not have much interest in other design aspects, BMS, or algorithms.

However, EST-Floattech, which develops eco-friendly, marine energy storage system technology and sells related products, seems to have more advanced marine energy storage system than any other companies in Korea. The marine energy storage system operates in a completely different environment from electric vehicles, which brings a great potential to EST-Floattech whose technology and capabilities are highly likely to be sought after by companies who wish to enter into similar fields of industry. Companies that have a potential to cooperate with EST-Floattech in Korea are a newly-established company by Goodbye Car (http://www.goodbyecar.co.kr/) to build eco-friendly boats and Hyundai Heavy Industries which manufactures large vessels.

(2) Second-use and Recycling (Circular industry, etc.)

Unlike internal combustion engine vehicles, electric vehicles do not have components/ materials with large economic values except used batteries. Wasted batteries contain toxic materials such as cobalt oxide, lithium, manganese, and nickel which may lead to heavy metal pollution or poisonous gas generation when exposed to outside of the battery. Second-use and recycling of used batteries has a significance in social and economic perspectives as they are also linked to the efforts to reduce the greenhouse gas mission and energy consumption.

To address these environmental issues and come up with viable solutions, countries around the world have been working on the establishment of management system for used batteries by revising the existing regulations or enacting new ones. With a gradual increase in the number of electric vehicles, there has been a growing interest in second-use and recycling of used batteries, and many companies have been launched in the related sector.

Table32. List of Second-use and Recycling Companies in Korea

Category	Companies
Second-use	Hyundai Motors Goodbye car PMgrow Poen AIMS, etc.
Recycling	SungEel Hightech Ecopro CNG Enerma PoscoHY clean metal Yongpoong(Korea Zinc), etc.

There has been a growing number of companies in Korea related to second-use and recycling of used batteries, but one of the issues commonly found among them is the fact that their facilities, either newly built or expanded, are not located in Korea, but mostly located in Europe and the US. In addition, the volume of electric vehicles sold is mostly from Europe, the US, and China. Given these, it can be naturally drawn to a conclusion that, for second-use and recycling of used batteries, it is necessary to cooperate with companies, not in Korea, but in Europe and the US where raw materials for second-use and recycling can be found. From this perspective, many opportunities for cooperation in the second-use and recycling sector are anticipated between companies in the supply chain of the Netherlands and Korea. Anticipated cooperation opportunities are as follows:

1) Collecting wasted batteries

2) Used battery diagnostic assessment

3) Logistics

4) Second-use application

5) metal recovery

(3) Next generation battery materials and production processes

The development of existing lithium-ion battery using materials in the liquid state can be mainly described in two different directions: one, by developing the existing 4 major materials (cathode/anode/separator/electrolyte) to reach a desired level of performance; and two, by converting to all-solid-state battery, regarded as battery of dream. The Dutch companies that seem to have a potential in these aspects are those who have the Atomic Layer Deposition (ALD) technology which has been developed and strongly secured based on many years of experience in semiconductors (e.g. SALD). Another potential can be found in replacing the previously used graphite anode material with silicon of which energy capacity is greater than graphite one. Lastly, a new opportunity for the Dutch companies can be found in all-solid-state battery.

(1) ALD Technology (Delft-IMP, SALD, etc.)

The road map for battery cell development mainly focuses on increasing the energy density per weight and lower the battery price. As a representative example, the evolution of cathode material has been heading towards to gradually increase the content of Ni instead of Co of which price is high. The chemistry currently used and commercialized is NCM811. Here, the chemical composition is 80% of Ni, 10% of Co, and 10% of Mn. Many cathode and battery companies have been striving for increasing the content of Ni, but in doing so they have faced several issues such as broken particles of cathode material. As one of the solutions to those issues, various coating technology has been adopted, and the ALD technology is among those potential technologies discussed and studied vigilantly.

If the Dutch companies with highly-advanced ALD technology can clearly identify their purpose of business and application of technology as well as prove their technical prowess with reliable test results, they are presumed to have great advantages in applying their ALD technology to cathode materials for battery. The ALD technology, in fact, is seen as something that can be applied in various ways to cathode materials and electrolyte for all-solid-state battery, too. The range of companies that may have interest in the ALD technology can be narrowed down to the K-trio battery companies, cathode material companies (Posco Chemical, LG Chemical, Ecopro BM, L&F, etc.), and coating facility companies (CIS, PNT, Hanwha Precision, etc.).

(2) Silicon Replacing Graphite (E-Margy, Leyden Jar Technologies, etc.)

In order to replace graphite used in battery, there have been numerous technical changes and significant developments in silicone, and taking the year of 2024 as a turning point, it is expected that more silicon anode materials are used for battery production. At present, due to the volumetric swelling issue, silicone is mostly used at around 10% (weight ratio) of graphite inside anode. To adopt more silicon to battery, a host of companies have been carrying out research. In the Netherlands, there are two companies that have developed their innovative idea to use 100% silicon for anode. As they are on the same path with the battery development roadmap, it is recommended that they should utilize their well-established knowledge and technical advantages to look for opportunities of cooperation.

(3) All-solid-state Battery (LionVolt, etc.)

Many companies around the world have been conducting the development of all-solid-state battery by utilizing a variety of ideas. In order to develop all-solid-state battery and commercially apply the technology to marketable products, companies from raw materials, manufacturing to facilities should all be in close cooperation and seamlessly create a supply chain from which they can meet the demand of consumers in terms of price and performance. Given the technical complexity and requirements for all-solid-state battery, any of the Dutch companies does not seem to be capable of solely working on an all-solid-state battery project. Rather, they are encouraged to find their partner company for joint cooperation to develop all-solid-state battery.

8.2 Recommendations for the Dutch industry and companies

In line with the carbon neutralization in Europe, the Netherlands has been putting a lot of effort into entering the secondary battery industry. The industry is linked to the entire ecosystem of battery from silicone (advanced anode material for battery), next-generation all-solid-state battery, second-use/recycling to battery system. As battery which has been often used for electronic devices is now used for electric vehicles and energy storage system for power grid, the entire volume has been increased exponentially, creating a huge market. What is more promising is the fact that a continuous market expansion is expected.

In fact, the secondary battery industry has not solidly secured its position yet. Many companies around the world are keen to utilize their capabilities and technologies in possession to preoccupy advantages in the market, which accelerates technology advancement. The supply chain for secondary battery has been solidly built based on such a large market demand and supply. Given all these circumstances and interviews with the Dutch companies related to secondary batteries, the following suggestions can be made:

1) Clear Definition of Business Model

The secondary battery industry in future is expected to be led by electric vehicles. The pack-module-cell-raw materials-equipment are all to be incorporated into the car industry sector. The car industry is an industry which places a great emphasis on the uniformity of product quality and the period of delivery. In other words, it is necessary to secure a qualified production facility in advance with quality and at a sufficient scale.

If a raw material is newly developed like silicone anode material, it usually takes a long time to get the quality of material verified and secure a production facility at a certain scale. Even if a company already has superior technology and products, it may take a long time to verify the quality of product or technology. Given these possible negative scenarios, a business model should be solidly established to prevent any Dutch company from suffering unnecessary delays or difficulties. It is recommended that they should pursue their effort to obtain official licenses of technology, establish joint ventures, and diversify business models.

2) Business Expansion Based on Items with Basis of Secondary Battery in the Netherlands

The Netherlands has long been known as a maritime power, building a variety of vessels, and already electrifying them. Even from the global perspective, it can be said that the nation is certainly in a leading position in the market.

Utilizing its advantageous position, if the Netherlands expands its industry sector in all directions, it may create an industry sector of which chance of success is high. For instance, battery cell for vessel, charger for vessel (assumed to have a different chargeable capacity from that of vehicles), and battery module/pack for vessel are all promising battery applications.

3) Preoccupation of Next-generation Market Based on Capabilities in Possession

The Netherlands, which has world’s leading semiconductor equipment companies, boasts the world’s leading coating technology. One of the representative coating technologies is the ALD technology, which is believed to be applicable to cathode, anode, and all-solid-state battery production process in the future. To materialize the application of ALD technology, it is recommended that the Dutch companies should seek for cooperation with the Korean companies or battery manufacturers in Europe that have more advanced battery-related technology.

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