Hans Böckler Stiftung

Mitbestimmung · Forschung · Stipendien

WORKING PAPER FORSCHUNGSFÖRDERUNG

Number 168, January 2020

Evaluation of Lithium-Ion Battery Cell Value Chain

Varvara Sharova, Paul Wolff, Benedikt Konersmann, Ferdinand Ferstl, Robert Stanek and Markus Hackmann

FORSCHUNGS-
FÖRDERUNG

Authors

Ferdinand Ferstl is a Consultant and Li-ion cell expert at P3 automotive, focusing on the raw materials and cost calculations.

Markus Hackmann is an Executive director at P3 automotive GmbH.

Benedikt Konersmann is a Consultant and Li-ion expert at P3 automotive GmbH, specializing on all-solid-state technology and manufacturing processes of Li-ion battery cells.

Dr. Varvara Sharova is a Consultant and Li-ion cell expert at P3 automotive GmbH, specializing on cell chemistry as well as supplier and test management.

Robert Stanek is a Global e-mobility advisor at P3 automotive GmbH.

Paul Wolff is a Consultant at P3 automotive GmbH with expertise in manufacturing processes of Li-ion batteries and e-powertrain components.

Hans-Böckler-Straße 39, 40476 Düsseldorf, Germany
www.boeckler.de

ISSN 2509-2359

Contents

Figures

Tables

Abstract

Li-ion batteries (LiB) have been widely employed in the various applications, including power tools and consumer electronics. Due to the rising awareness of climate change and the rising penalties for CO_2 emissions, electric vehicles with traction LiBs are considered an elegant solution. In an electric vehicle, the battery comprises 30 to 40 percent of the total cost and is considered one of the most complex components in terms of technology.

Modern Li-ion batteries are currently produced mostly by Asian manufacturers, who are also penetrating the European market. However, prognosed demand for electric vehicles in Europe cannot be met just by the existing production capacity. This gives the new European players an opportunity to enter the market and establish local value chains.

The Li-ion battery value chain consists of the six main stages, which include extraction of raw materials, synthesis of active battery cell materials, manufacturing of electrodes and cells and, finally, recycling. The stages related to the cell module and pack assembly are not covered here as they are out of the scope of the current study. For each value chain stage, we determined the main challenges and success factors and emphasized the required competences. Furthermore, the main players have been evaluated based on their production capacities and experience. As followed from the evaluation, to allow uninterruptable supply the upstream integration is beneficial. Furthermore, cooperation with other players is essential to attain a competitive position in the market. Based on that analysis, we propose a partner network with focus on Germany/France for each stage of the LiB value chain.

Introduction

CO_2 emission goals set by European Commission (Reducing CO2 emissions from passenger cars, 2009) require an increasing electrification of the automotive original equipment manufacturers' (OEM) vehicle fleets. Unlike internal combustion engine vehicles, the traction battery is the key element in electric vehicles in terms of required know-how and value added. From a technological and financial point of view the decisive factor is the performance of the Li-ion batteries (LiB), which are nowadays mostly being manufactured by Korean, Chinese and Japanese manufacturers. The expected ramp-up volume for electric vehicles caused by the demand for emission-free mobility will require LiB cell market growth of several hundred GWh by 2025 – a volume that will give new manufacturers the opportunity to enter the market.

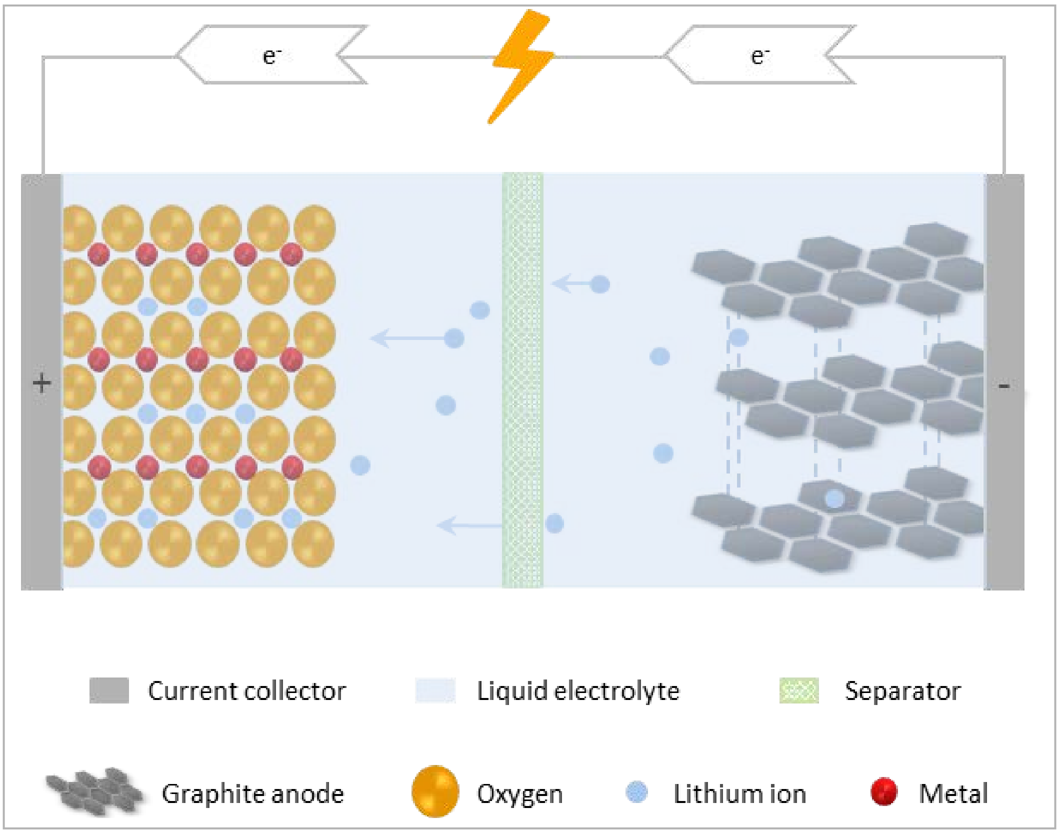
To enter this, market European/German players will have to utilize existing expertise along the entire battery value chain to catch up the existing backlog to the market leaders from Asia. Therefore, it is necessary to select the relevant network partners of the value chain in a field analysis and evaluate them with respect to their expertise, know-how and experience.

In this working paper all stages of the Li-ion cell value chain are described consecutively – from the raw material extraction to the recycling of cell components. The existing market players and the most important competences are identified for every stage of the value chain. Based on that, possible network partners in Europe (with focus on Germany/ France) are highlighted.

Basics of Lithium-Ion Battery Cell

For a better understanding of the production steps of the Li-ion battery cell, it is essential to get acquainted with its working principle and its main components. Li-ion cell consists of two electrodes. The negative (anode) is casted mostly on the copper foil, whereas the positive (cathode) is casted on aluminum foil. A thin electron-insulating layer (aka separator) soaked with the electrolyte (liquid ion-conducting media) separates the two electrodes. Upon charging the lithium ions, extracted from the cathode, are shuttled through the separator/electrolyte and intercalated into the anode. At the same time, the electrons are flown in the same direction through the external circuit. On discharge, as shown in Figure 1, the opposite process takes place, providing the electrical power.

Figure 1: Working principle of a Li-ion cell (upon discharge)



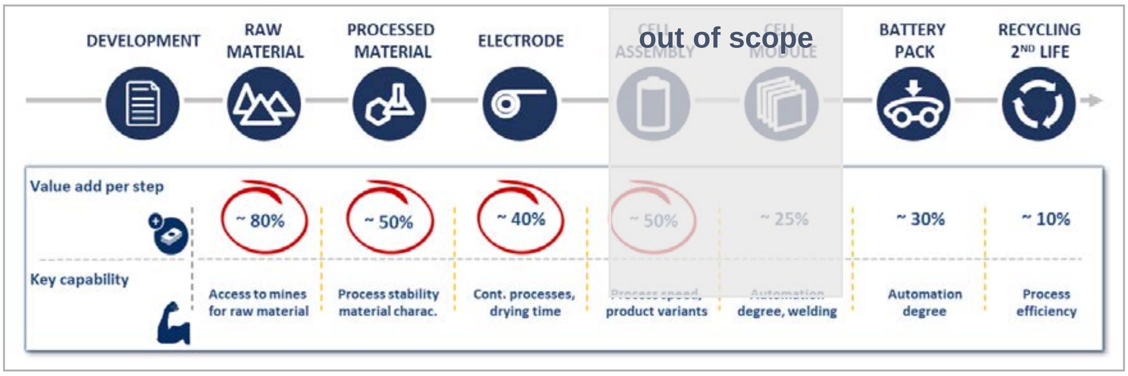
Source: P3 own representation.

As anode material graphite is mostly used, whereas lithium metal oxides $LiMO_2$ (i.e., $LiNi_xMn_yCo_zO_2$) are commonly employed as cathodes. Electrolyte represents a mixture of organic solvents with a Li-conducting salt dissolved in it. Finally, polymeric membranes or non-woven fabric mats are the materials of choice for the separators. Li-ion cells are typically available in three main formats, which will be in detail described in one of the following chapters.

Lithium-Ion Value Chain Evaluation

The Li-ion cell value chain represents a closed loop from the raw materials extraction to the recycling of the cells. An overview of the value chain is shown in Figure 2. As also marked in the figure, first four steps of the value chain have the highest value added due to their complexity and necessary know-how. The individual stages of the value chain will be analyzed separately in the following. The value chain steps „cell module“ and „battery pack“ will not be discussed in the paper.

Figure 2: Overview of the Li-ion battery cell value chain stages



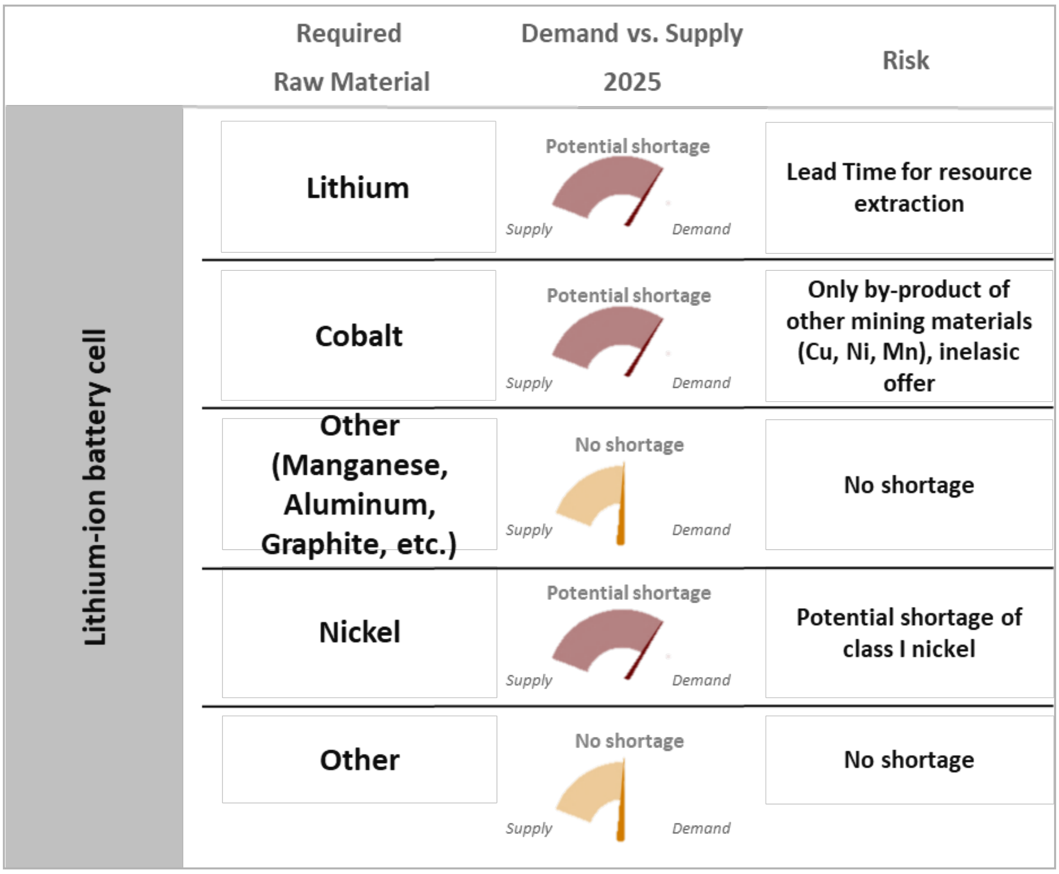
Source: P3 own representation.

Raw Material

Incorporating a value add of approximately 80 percent from ore extraction to refined metal salts, raw material extraction stage plays a critical role within the value chain of Li-ion battery cells. The key factor in this stage is the access to the appropriate mines. Additional success factor for the players in this stage includes the deep understanding of the extraction processes of raw materials from mine ores. Ongoing research on novel materials must be considered as well.

One of the key challenges of raw material extraction is the availability of ore deposits, which are also unevenly spread among the resources. As illustrated in Figure 3, the main cathode precursors, namely, lithium, high-grade nickel and cobalt may show a potential shortage. As the raw material extraction is currently no core competence of automotive OEMs, they strongly depend on mining and material companies, which request high margins especially for the scarce materials. Furthermore, the construction of new mines (i.e., for lithium and cobalt) relates to long ramp-up times and complex licensing processes.

Figure 3: Overview of the materials availability for Li-ion cell production



Source: P3 own representation.

Many raw materials are geographically concentrated in politically unstable regions. For example, mining of cobalt is dominated by Democratic Republic of the Congo (DRC; >60 percent of the world's mining), where the working conditions, including child labor, are not strictly controlled (Siddharth Kara, 2018). To ensure ethical supply of this material, high transparence of the whole value chain and its tracking are necessary.

Cobalt is mostly extracted as a by-product from nickel (50 percent) and copper (44 percent) mining industries (Cobalt Institute). As mentioned above, the largest cobalt producers are located in DRC as presented in Table 1, whereas the refinement is dominated by Chinese companies, illustrated in Table 2. In 2016–2018, cobalt price increased by over 300 percent (Lithium and cobalt prices to remain under pressure as supply overtakes demand – report, 2019). This drastic price increase was related to the inadequate reaction of the market towards the growing demand of electric vehicles and mining companies seeking for a profit from these geographically localized reserves. However, in 2019 cobalt prices have fallen due to the increasing number of mining suppliers (Sanderson, 2019) and shift to the materials with low cobalt content. Nonetheless, a new boost in cobalt prices due to mismatch of demand and supply is not excluded (*Why have Cobalt Prices crashed*, 2019).

Table 1: Top cobalt mining companies

Company name	**Mining location**	**Mining capacity (t/a)**	**Market share**
Glencore	DRC, Australia	42200	30 %
China Molybdenum	DRC	16800	12 %
Jinchuan	DRC	8400	6 %
Norilsk Nickel	DRC, Russia	7000	5 %

Source: Distribution of cobalt production worldwide in 2016, by company, 2016; Cobalt Statistics and Information; Cobalt Institute; Berman et al., 2018.

Table 2: Top cobalt refining companies

Company name	**Refining location**	**Refining capacity (t/a)**	**Market share**
Huayou	China	17800	15 %
Freeport Cobalt	Finland	12900	10 %
Jinchuan	China	12700	10 %

Source: Cobalt Institute; Here are the firms feeding China's battery revolution; Berman et al., 2018.

After development of large-scale lithium brine operations in South America (aka „lithium triangle“) in 1980's (O'Brien et al., 2016), it has become a predominant source of this metal, followed by Australian spodumene production (The lithium-ion battery value chain. New Economy Opportunities for Australia, 2018). Strong oligopolistic supply situation in the market is especially pronounced for lithium extraction. As also shown in Table 3, the four biggest mining companies control 77 percent of the lithium market. In lithium refinement, like for cobalt, China is constantly enhancing its capabilities (Azevedo et al., 2018).

Table 3: Top lithium mining companies

Company name	Mining location	Mining capacity (t/a)	Market share
Albemarle	Australia, Chile, U.S.	73000	31 %
SQM	Chile	50000	21 %
Tianqi	Australia	40000	17 %
FMC	Argentina	19000	8 %
Galaxy Resources	Australia	15000	6 %
Jiangxi Ganfeng	Australia	11000	5 %

Source: The lithium-ion battery value chain. New Economy Opportunities for Australia, 2018; Berman et al., 2018.

Until now nickel market has been dominated by the established steel industry. However, due to the shift to Ni-rich cathode materials, the demand for this metal is expected to grow drastically (Bernhart, 2019). This is because only so called „1st class nickel“ is suitable for battery production. Mining of this high purity material is economically reasonable from the sulfidic ore deposits (Bohlsen, 2019), which comprise only 40 percent of the total nickel reserves. Overall, nickel market is more fragmented, where mining and refining are often done by the same company, as presented in Table 4 and Table 5.

Table 4: Top nickel mining companies.

Company name	Mining location	Mining capacity (t/a)	Market share
Vale	Brazil, Canada, etc.	248000	21 %
Norilsk Nickel	Russia	201000	17 %
Glencore	South Africa	106000	9 %
Jinchuan Group	DRC, Zambia, South Africa, China	83000	7 %

Source: The lithium-ion battery value chain. New Economy Opportunities for Australia, 2018; Berman et al., 2018.

Table 5: Top nickel refining companies

Company name	Refining location	Refining capacity (t/a)	Market share
Vale	Brazil, Canada, etc.	236000	21 %
Norilsk Nickel	Russia	212000	19 %
Glencore	Canada	138000	12 %

Source: The Li-ion Battery Value Chain. New Economy Opportunities for Australia, 2018; Berman et al., 2018.

Manganese extraction is also dominated by the steel industry (approximately 90 percent), followed by the use for primary and rechargeable Li-ion batteries (Boubou, 2019). Global reserves of manganese comprise around 690 million tons, and are mostly located in South Africa, Australia and India (European Commision Report on Raw Materials for Battery Applications, 2018) as shown in Table 6. Manganese refinement in turns is dominated by Ukrainian and Chinese companies, as show in Table 7. Price of this material remains on a constantly low level. Furthermore, no massive production bottleneck from other industries is expected. All these leads to the conclusion that manganese does not belong to „critical“ materials for LiB production.

Table 6: Top manganese mining companies

Company name	Mining location	Mining capacity (kt/a)	Market share
South32	South Africa, Australia	5541	28 %
MOIL	India	2700	13 %
Vale	Brazil	1825	9 %
ERG	Kazakhstan	360	2 %

Source: South32 2018 Financial Results, 2018; Vale Annual Reports; ERG Manganese Ore Concentrate; Mazumdar, 2019.

Table 7: Top manganese refining companies

Company name	**Refining location**	**Refining capacity (kt/a)**	**Market share (%)**
Hongxin	Ukraine	NA	–
Hunan Dongfang	Ukraine, China	NA	–
Ningxia	China	NA	–

Source: Manganese – the third electric vehicle metal no one is talking about, 2017; European Commision Report on Raw Materials for Battery Applications, 2018.

Graphite being the state-of-the-art anode material can be divided into natural and synthetic. Whereas natural graphite is extracted from ore, synthetic one is produced from petroleum coke or tar pitch. China is the global leader for the natural graphite supply with approximately 69 percent market share, followed by India and Brazil (European Commision Report on Raw Materials for Battery Applications, 2018) as Table 8 shows. Approximately 70 percent of the mined material accounts for amorphous graphite, and only 30 percent for flake graphite, which is the only one to be used as anode material in LiB (Benchmark Mineral Intelligence – Graphite price assessment, 2018).

Table 8: Top graphite mining companies

Company name (extract)	**Mining location**	**Mining capacity (mt/a)**	**Market share**
China Carbon Graphite Group	China	780000	69 %
Arunachal Pradesh	India	150000	12 %
Extrativa Metalquimica	Brazil	95000	8 %
SRG Graphite	Canada	30000	3 %

Source: The Li-ion Battery Value Chain. New Economy Opportunities for Australia, 2018.

From the analysis of the raw material stage of the LiB value chain it can be concluded that mining of certain critical materials is geographically localized and oligopolized. Furthermore, a clear leadership of Chinese companies can be observed in the refinement sector. Europe is using its resources to small extent (European Commision Report on Raw Materials for Battery Applications, 2018; Raw materials scoreboard European innovation partnership on raw materials) and the dependency on imported materials will increase in local battery factories. As the demand for some resources is critical or is prognosed to become short, the European companies must secure the value chains to enable the uninterruptable supply.

Material Production

Material production is strongly linked with the raw material sourcing. To avoid possible shortage of the required sources due to a constantly increasing worldwide demand on batteries, a trend towards the reduction of critical or scarce materials can be observed in the Li-ion market. Moreover, cell manufacturers increasingly consider upstream value chain integration to secure the supply.

Market structure within this stage is very complex and not completely transparent. Another challenge is the instability in the prices of the critical raw materials, which was already discussed in the previous chapter. A rise of new players for „low-tech“-materials (like graphite) could be observed in a market, thus, leading to a high level of competition. Moreover, development of next generation materials (e.g., required for all-solid-state technology) might cause risks in view of their higher complexity compared to state-of-the-art ones and/or the need for substitution of active materials (i.e., from graphite to Li-metal) or inactive components (i.e., from liquid to solid-state electrolyte).

Success factors for key players in this stage include upscaling with constant material quality that is necessary for further cost reductions. Furthermore, development of new synthesis routes with higher material output and lower number of production steps is beneficial. Continuous quality control of the materials and the used machinery are mandatory to fulfill established specifications and ensure uniform cell performance.

Lithium nickel cobalt manganese oxide, also known as NMC has been established as the state-of-the-art cathode material thanks to its high operating potential *vs* lithium and high theoretical capacity. By increasing the amount of Ni in the material (i.e., from NMC111 with equal parts of Ni, Mn and Co to NMC622 with the ratio of Ni:Mn:Co of 6:2:2), the capacity can be further elevated but at the expense of moderate cycle life and safety compared to NMC111 (Noh et al., 2013). Table 10 presents an overview of the key players within the NMC production process. As follows from Table 9, current key players in the market are the cell manufacturers themselves as well as Asia-based companies. As cell manufacturers possess know-how for cathode material synthesis, there is a strong trend that shows an upstream integration of the cathode material production within the value-chain to secure supply, utilize the cost potentials and develop new technological USPs.

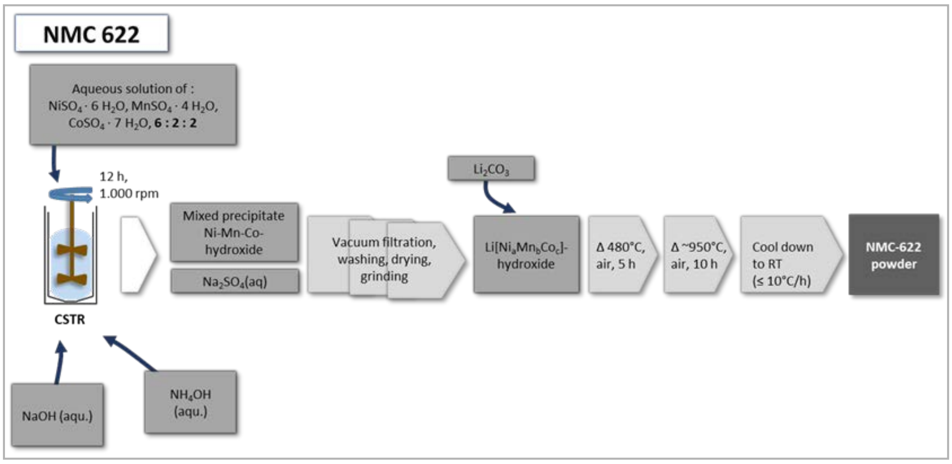
Table 9: Top NMC manufacturers

Company name	**Manufacturing location**	**Market share**
Internal (from cell manufacturers)	–	14 %
Umicore	Korea	12 %
Hunan ShanShan	China	12 %
Xiamen Tungsten	China	10 %
Nichia	Japan	9 %
L&F	China	9 %

Source: P3 analysis.

NMC622 is currently considered as a cathode material of choice, enabling increase in the cell energy density and reduction of cobalt content in comparison to its predecessor, NMC111. Figure 4 illustrates the production process of this cathode material. As a first step aqueous solutions of nickel, manganese and cobalt and different solvents are mixed in a continuous stirred-tank reactor (CSTR). As a result, Ni-Mn-Co hydroxide precipitates from the solution. After certain vacuum filtration, washing, drying, grinding, addition of lithium precursor (Li_2CO_3) and calcination, the NMC622 powder, which can be further modified with respect to the particle morphology, particle size and/or surface coating. For other chemistries with even higher Ni concentrations, such as NMC811 and lithium nickel cobalt aluminum oxide (NCA), $LiOH{\cdot}H_2O$ is used as a precursor instead of lithium carbonate, as it leads to enhanced physical properties and improved material crystallinity (Fitch/Yakovleva, 2017).

Figure 4: Overview of NMC synthesis



Source: P3 own representation.

Graphite has been used as an anode material since more than 20 years due to its low potential *vs* Li/Li$^+$, high electronic conductivity and relatively high specific capacity. A wide range of graphite materials including natural, synthetic and composite ones is currently used as anode materials. Whereas natural graphite offers a cost advantage, the cell performance can be improved with the synthetic graphite; a blend of two materials enables the balance of both characteristics (Verner, 2017).

Table 10 presents an overview of the key natural graphite manufacturers. As shown in the table, production of natural graphite is concentrated in Asia. China is dominating the market with approximately 49 percent share, thus controlling the significant part of the value chain.

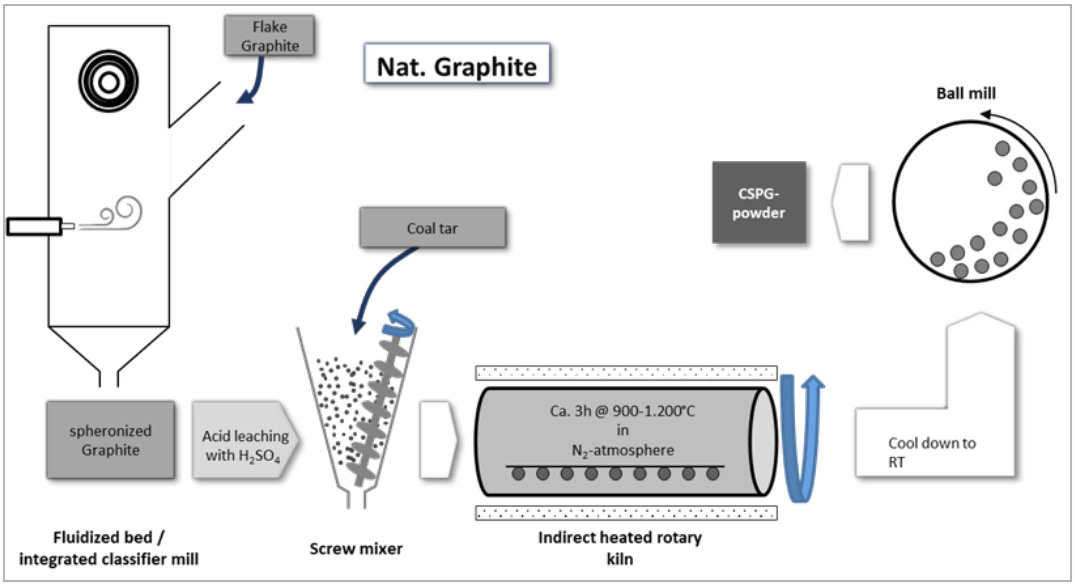
Table 10: Top natural graphite manufacturers

Company name	**Manufacturing location**	**Market share**
BTR	China	49 %
Mitsubishi	Japan	16 %
Hitachi	Japan	11 %
Nippon Carbon	Japan	4 %
POSCO Chemtech	Korea	4 %
Others	–	16 %

Source: P3 analysis.

In Figure 5 the exemplary process of natural graphite manufacturing is depicted. First, raw material (flake graphite) is placed in an integrated classifier mill. The resulting spheronized graphite powder is leached with sulfuric acid and mixed with coal tar in a screw mixer. Then in an indirectly heated rotary kiln, the material is dried under N_2-atmosphere at approximately 900 °C to 1200 °C for three hours. After a cooling down to room temperature (RT) the powder is ball-milled resulting in a coated spherical purified graphite (GSPG).

Figure 5: Overview of the natural graphite synthesis



Source: P3 own representation.

Synthetic graphite is manufactured by thermal treatment of amorphous carbon (i.e., calcined petroleum coke or tar pitch) (Dante, 2016). Major synthetic graphite manufacturers are listed in Table 11. With a market share of approximately 56 percent among four different companies Japan is competing with China for the dominancy in this sector.

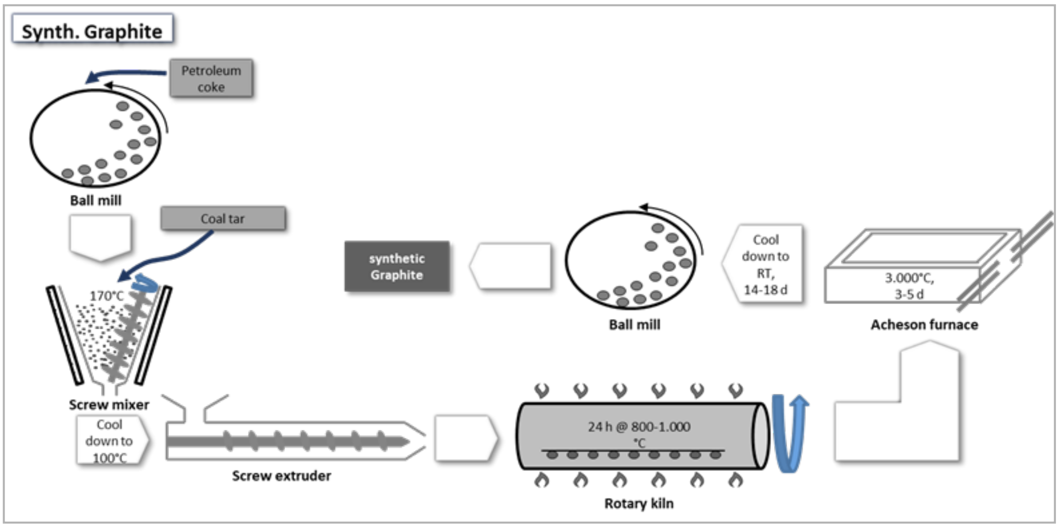
Table 11: Top synthetic graphite manufacturers

Company name	Manufacturing location	Market share
Shanshan	China	38 %
Hitachi	Japan	31 %
JFE	Japan	11 %
Mitsubishi	Japan	9 %
Showa Denko	Japan	5 %
Others	–	6 %

Source: P3 analysis.

Figure 6 shows the overview of the synthetic graphite production process. In the first step a precursor (petroleum coke in this case) is ball-milled. The grinded powder is mixed with coal tar in a screw mixer at 170 °C. Resulting material is dried in an indirectly heated rotary kiln for 24 hours. Afterwards the Acheson process (graphitization of the amorphous material under temperatures up to 3000 °C) is run for three to five days, enabling high purity of the outgoing material. After cooling down and another grinding step, the synthetic graphite is obtained.

Figure 6: Overview of the synthetic graphite synthesis



Source: P3 own representation.

As also noticed for the materials extraction, core competence in synthesis of Li-ion cell active materials is concentrated in Asia. Whereas to produce cathode material various cell suppliers use in-house competence, both natural and synthetic graphite materials are manufactured by third parties. Despite the lower cost of the natural graphite, the growing demand for this material can be effectively supported by the synthetic one, also adding benefits in electrochemical performance.

Electrode Manufacturing

Electrode manufacturing process generally consists of six steps including mixing of electrode active and inactive materials (forming a slurry), coating of the slurry on the current collector, drying, calendaring, slitting and an additional (vacuum) drying. The steps and related value-added are displayed in Figure 7.

Figure 7: Overview of the electrode manufacturing process steps

Source: P3 own representation.

Among challenges in this stage one can mention in-line control of the quality parameters as well as building and maintaining the atmospheric environment. Increasing the process speed while ensuring a consistent high quality is yet another challenge for many companies in this value chain stage. To comply with the existing norms efficient reutilization and recycling of the organic solvent used for the slurry preparation is necessary. Furthermore, process changes due to upcoming new technologies and materials like solid-state, solvent-free electrode processing or in view of silicon anode material need to be considered. Due to rising demand various cell manufacturers are opening new production sites close to their potential customers. The equipment transfer and installation as well as the localization of the new plants and staff qualification must be carefully planned to enable uninterruptable production with the same quality. Nevertheless, each new manufacturing site requires an extensive ramp-up phase with production and quality parameters slowly reaching the required standards.

To be successful in this stage players must force cost reduction to ensure competitiveness. This can be achieved through the improvement of all electrode manufacturing steps. However, the implementation of innovative technologies is tangled through fast production ramp-up and cost pressure. Due to the rising demand for improved cell performance, companies must orientate towards electrode optimization to reduce the internal resistance and increase energy density of the battery cells. In view of varying cell dimensions, the design of the equipment should ideally allow a rapid switch between them. Table 12 lists several players acting in this stage and the equipment manufacturers, supplying machines for the electrode production.

Table 12: Electrode production market participants and equipment manufacturers

Market participants (HQ)	**Equipment manufacturers (HQ)**
Nichia (Japan)	Hanwha (South Korea)
Umicore (Belgium)	Hibar (Canada)
Mitsubishi Electric (Japan)	Eirich (Germany)
Hitachi (Japan)	Bürkle (Germany)
Sumitomo (Japan)	Kroenert (Germany)
DOW (USA)	Dürr Megtec (Germany)
Pulead (China)	Coatema (Germany)

Source: P3 analysis.

Besides active materials, described in the previous section, which supply or host Li-ion during charge/discharge processes, various inactive components are present in the electrode. To ensure good adhesion of the slurry, a binder (usually a polymeric material), is used during electrode preparation. Conductive agent (usually a carbonaceous material), in turns, allows improvement in the electronic conductivity of the active materials, providing pathways for fast electron transfer. Finally, current collector is a metal foil, on which the electrode slurry is casted, which allows shuttling of electrons.

Among the cell inactive components, separator and electrolyte play a significant role in the overall cell performance. The former one enables the transfer of Li-ions while preventing the physical contact of two electrodes to avoid short circuit; whereas the latter is the organic media providing conductive pathways for Li-ion movement. The extract of the inactive materials suppliers is presented in Table 13.

Table 13: Overview of the inactive materials suppliers (extract)

Electrolyte material suppliers	**Separator material suppliers**	**Other material suppliers (binder, conductive additive, tape, etc.)**
3M	SK Innovation	Tesa
BASF	AsahiKasei	3M
UBE	Evonik	DOW
Tinci	Treofan	Targray
Capchem	Freudenberg	Schlenk
Shanshan	Sumitomo	Sumitomo
Guotai-Huarong	Toray	Imerys
Panax Etec	Celgard	NEI

Source: P3 analysis.

To summarize, electrode manufacturing process is very complex, requiring strict control of the production environment and the precise setting of process parameters to allow homogeneous thickness of the electrode sheets. Although prominent cell manufacturers establish electrode lines in-house, various companies, dominated by Japan, are offering the ready electrodes. Worth mentioning is that among established equipment manufacturers, providing machinery for electrode production lines, are several Germany-based players, offering energy saving solutions and high-quality products.

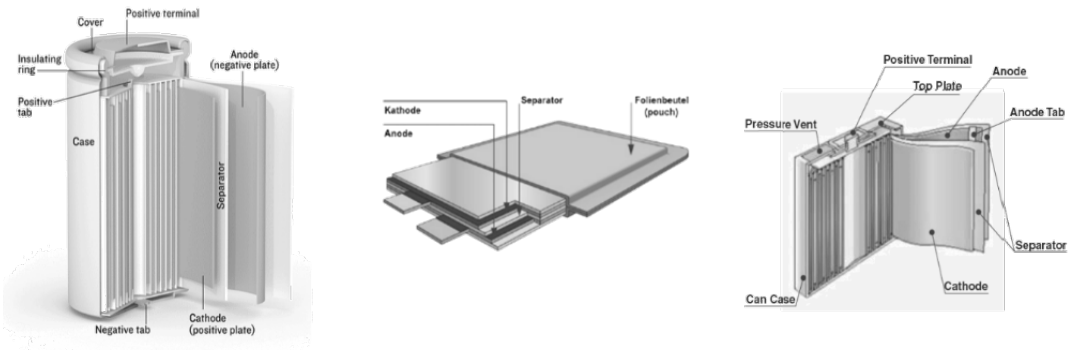
Cell Manufacturing

Cell assembly, following the electrode manufacturing, is another complex process, consisting of several steps. It requires a very strict control of the production environment to avoid high moisture content in the finished cell. This is because traces of water can react with the electrolyte components, leading to rapid performance decay of the finished cells.

Cell manufacturing capabilities are dominated by Asian companies due to their valuable experience, also gained in the consumer electronics and in the first automotive projects. Increasing the production speed (and resulting cell output) without any losses in the cell quality is vitally important. Furthermore, due to political and social requirements, players should move towards sustainable energy sources for their production facilities.

Depending on the application three different formats for LiB are currently available. These include cylindrical, prismatic and pouch format (button cells are excluded as they are mostly non-rechargeable), with each having certain advantages and disadvantages. The formats are schematically shown in Figure 8.

Figure 8: LiB cell formats: cylindrical (left), pouch (middle), prismatic (right)



Source: Wiebelt et al., 2009.

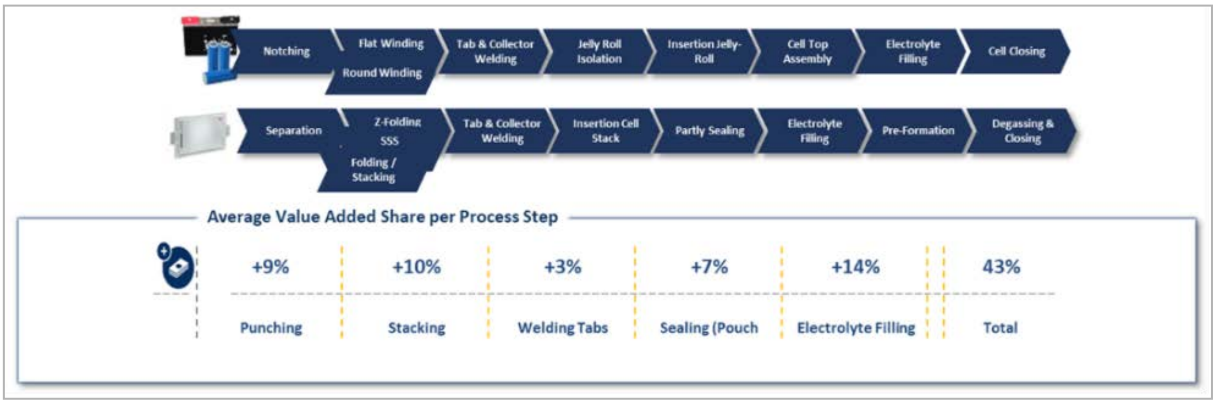
Cylindrical Li-ion cells come in various standardized sizes and are based on the well-known cells 18650 (the first two digits indicate the diameter in mm, the following three digits define the length of the cell body in mm) that first powered the consumer electronics in 1990's and was later adopted for automotive applications. Other commonly used formats include 20700 and 21700. One of the most famous use-cases in automotive applications is Tesla/Panasonic with NCA chemistry. One of the main advantages of the cylindrical cells is the highest energy density among the three available formats but at expense of relatively low energy to volume ratio. Cylindrical cells allow flexible battery design due to parallel connection of a high number of cells. On the other hand, the packaging design is more complex compared to other formats and the energy density on the pack level is the lowest among the three formats. Although the mostly utilized NCA chemistry in this format shows disadvantages in terms of safety and lifespan, cylindrical format has reached its technological maturity, enabling one of the lowest prices per kWh.

Prismatic cells are tailored specifically for automotive application. Exemplary use-cases include various battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Prismatic cells possess high mechanical integrity and can be easily inserted into a battery pack. Also, it is a safest cell format currently present in the market. However, its low cell-level energy density compared to cylindrical format in combination with costly housing is rather disadvantageous.

Just like prismatic, pouch cells are usually customized for the corresponding use-case as no standard sizes exist. For example, the batteries of Renault Zoe consist of pouch cells, manufactured by LG Chem. Generally, pouch cells enable high energy density at the cell level, depending on the selected chemistry. These cells are lightweight, flexible and simple. As a result, a low-cost mass production can be achieved for the pouch format. However, these cells are more sensitive to humidity and elevated temperatures. Furthermore, cell swelling upon lifetime is of high concern, leading in the worst case to the damage of the whole battery.

The differences in the design of the three formats is also reflected in the manufacturing processes, as also shown in Figure 9. Cylindrical and prismatic cells contain so-called „jelly roll", the wound stack of anode and cathode sheets with separator in between. Pouch cell, in turns, consists of the stack of single electrodes, which are cut prior to the cell assembly and are either stacked together with separator sheets in between or inserted into the running separator „pockets" during z-folding (Schröder/Aydemir/Seliger, 2017).

Figure 9: Overview of the cell assembly steps using three cell formats

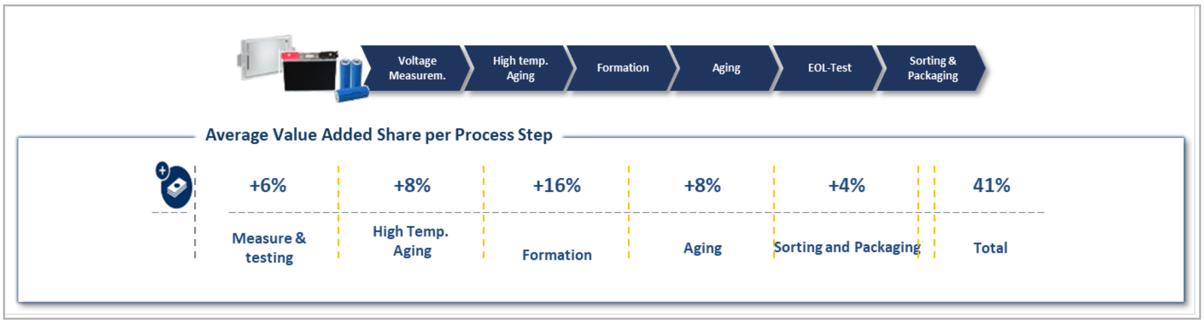


Source: P3 own representation.

Insertion of the jelly roll in the cell is generally more complicated as care needs to be taken to prevent the jelly roll damage. In case of pouch cell, the stack is placed into the pre-shaped half of pouch foil, covered by another half and sealed from three sides. In the next step the cell is filled in with the electrolyte, sealed and transported into the formation facility.

Term „formation“ refers to initial cycling of the cell using relatively small currents combined with aging at elevated temperatures to enable the formation of passivation film on the graphite anode surface and gas generation, which is then released either through the pressure valve for hard-case cells or through the additional gas pocket of the pouch cell. Formation of the cells is conducted by the cell manufacturer in-house, which is related to additional costs and requires special facilities. Generally, formation protocols are based on the intensive preliminary testing and remain confidential. The formation process can last up to three-four weeks and during this time, as also shown in Figure 10, several electrical measurements are conducted to sort out the cells with inadequate quality.

Figure 10: Overview of the formation and aging process steps



Source: P3 own representation.

Table 14 summarizes the top cell manufacturers and machinery providers for cell assembly and formation/aging. Due to strategical cooperation with Tesla Panasonic with its cylindrical cells has gained a strong position in the world market. Most of the top players have either already built the production plants in Europe to decrease the logistics costs or have announced to do so.

Table 14: Overview of the cell assembly value chain participants and equipment manufacturers

Market Participants (HQ)	**Equipment Manufacturers for cell assembly**	**Equipment Manufacturers for formation and aging**
LG Chem (South Korea)	Hibar	Maccor
Panasonic (Japan)	Manz	Manz
SK Innovation (South Korea)	Trumpf	Bitrode
Samsung SDI (South Korea)	NAT	Digatron
BYD (China)	ATS	ATS
CALB (China	Harro Höfliger	PEC
CATL (China)	Jonas & Redmann	Chroma

Source: P3 analysis.

As for the equipment manufacturers, despite the leading role of Asian players European manufacturers are also able to contribute to the market due to their geographically preferable production facilities (Schlick et al., 2011). One of the biggest challenges is related to the focus of equipment manufacturers on some specific process step(s) with only a few offering the complete assembly line. However, due to continuous improvement of the current technology, introduction of new solutions and close cooperation with Tier I and Tier II suppliers, this challenge could be overcome (Meiser et al., 2014).

To conclude, cell manufacturing process requires careful set of parameters and control of the production environment. Each cell format, currently available in the market of rechargeable batteries, has its benefits and limitations, which need to be considered for the pack design. Despite strong position of Panasonic with cylindrical cells for automotive application, pouch and prismatic cells are expected to be preferred in the future. Asian machinery providers are still overtaking the European ones due to the long-lasting relationships with Asian cell manufacturers and experience collected in the consumer electronics sector.

Battery Cell Recycling

Battery cell recycling is gaining increasing attention and focus of numerous research studies due to the disputes on Li-ion environmental sustainability. Up-to-date no standardized process to recover raw materials from batteries in a good cost-benefit ratio exists. Hydrometallurgical and pyrometallurgical processes are two dominant recycling methods currently utilized. Whereas pyrometallurgical process enables direct winning of metals and high productivity, hydrometallurgical route is a high-selective, high-efficient with low emissions of gasses. Among the limitations of pyrometallurgical route one can name the intensive use of energy and required control of emissions. The main disadvantages of hydrometallurgical recycling include the use of chemicals and high water and the necessity of waste water treatment (Friedrich et al., 2017). The two processes are often combined, which is, for example, implemented by Umicore Recycling (Elwert et al., 2015). Table 15 compares the recycling efficiencies of various elements from NMC and LFP cells using both methods.

Table 15: Recycling efficiency for various elements and selected methods for NMC and LFP chemistries

Material	**Combination of pyrometallurgical and hydrometallurgical processes (NMC and LFP)**	**Purely hydrometallurgical process (NMC only)**	**Purely hydrometallurgical process (LFP only)**
Lithium	57 %	94 %	81 %
Nickel	95 %	97 %	NA
Manganese	0 %	~100 %	NA
Cobalt	94 %	~100 %	NA
Iron	0 %	NA	0 %
Phosphate	0 %	NA	0 %
Natural graphite	0 %	0 %	0 %

Source: P3 analysis.

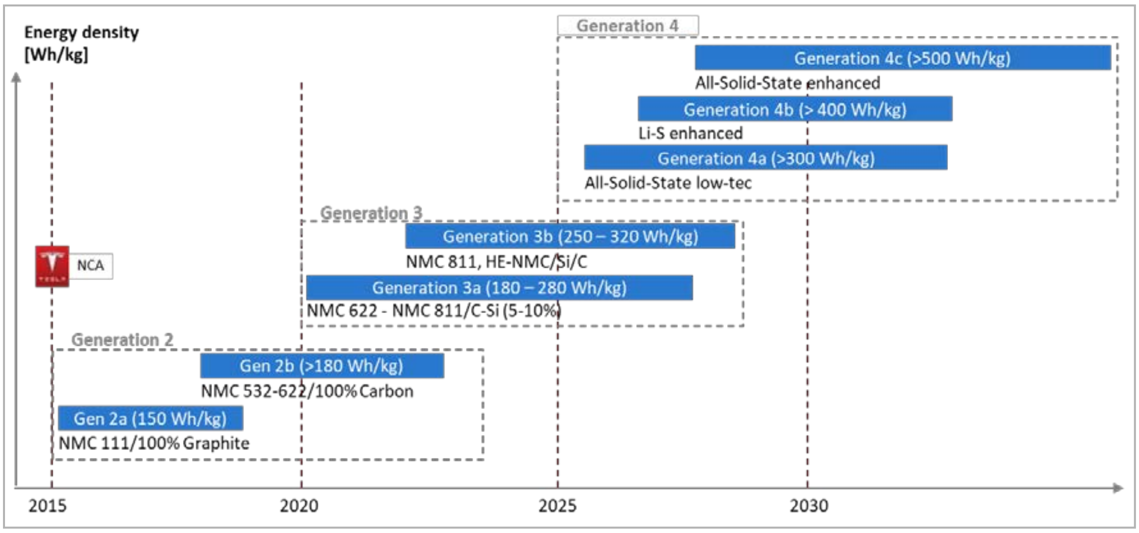
As follows from the table, only several metallic components of the cell can be efficiently recycled, resulting in total recycling rate of 50 % (Gupta, 2019). This is a relatively low rate when compared, for instance, with lead-acid battery, which is mostly used for engine start-stop, and whose recycling rate in Europe and USA exceeds 95 percent (International Lead Association, 2014).

In conclusion, with the growing energy density of the cells the safety requirements during the recycling process also increase. Additionally, there is a strong need in regulation of a long-range transport of used or defect cells. On the other hand, integrating the recycling processes into future production set-ups as a closed loop is the key for a consistent material supply and cost optimization (i.e., 80 percent of lead-acid batteries consist of recycled components (The Advanced Lead-Acid Battery, 2017). To facilitate this, the implementation of recycling standards is essential. Such standardized recycling route must be available for different chemistries, must be cost effective and sustainable. Thus, further research on novel and optimization of the existing recycling methods is mandatory. This effort might be advantageous especially for European recycling companies as the industrialized service could be offered also to Asian competitors.

Market Insights and Selection of Partners for Future Collaborations

Current Li-ion cells possess energy densities up to 250 Wh/kg (on cell level), with a prototype cell from CATL exceeding 300 Wh/kg (Xinhua, 2019). However, due to growing demand on longer driving ranges, further increase in energy density is desired. Various research bodies but also R&D departments at both cell manufacturing companies and OEMs are concentrating their efforts on improvement of the presently employed materials and the development of the novel ones. Technology roadmap of current and upcoming Li-ion cell generations is shown in Figure 11. Today's state-of-the-art technology includes NMC622 as cathode combined with graphite anode. Gradual energy density increase is prognosed for the upcoming generations. Up to generation 3, the focus of improvement will be on cathode material and electrolyte composition. Starting with generation 4a in ca. 2025 (all-)solid-state batteries are announced by several cell manufacturers and automotive OEMs. However, until now no test results on large-format cell- or pack-level are available for this technology. Major challenges like fast charging capability and wide operation temperature window remain unsolved. Generation 4b might focus on Li-sulfur batteries, allowing significant increase in energy density and low environmental impact and potentially low costs due to abundancy of sulfur. However, the high uncertainty for technological breakthrough with this chemistry is related to the unsolved problems, including fast decay due to „polysulfide shuttle“, large volume expansion during charge/discharge cycling and poor electronic conductivity of sulfur.

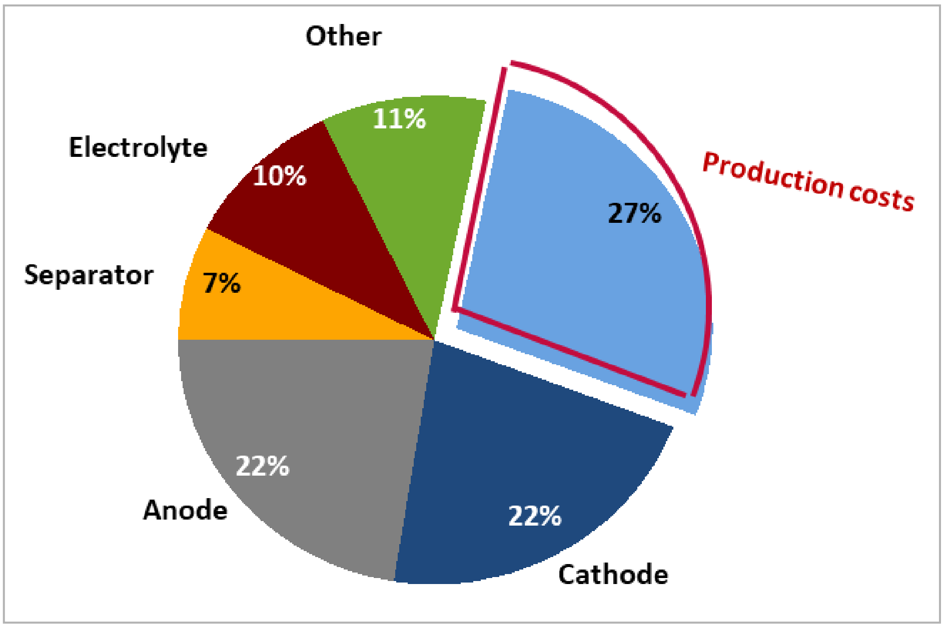
Figure 11: Technology roadmap of Li-ion cell generations



Source: P3 own representation.

Figure 12 illustrates an exemplary cost breakdown of an average NMC622 pouch cell design. As follows from the diagram, the highest proportion of costs accounts for production, followed by the active materials. One way to decrease these costs is to transfer the production closer to the possible in this case European customers, as, for example, LG Chem, Samsung SDI and CATL did. First learning curve effects and gradual production improvements enable ongoing cost reductions in labor, energy, available space, etc. According to P3 evaluation, such transfer could decrease lead times by approximately six weeks and reduce the logistics costs by around 25 percent.

Figure 12: Example of an advanced cell technology cost breakdown – NMC622 pouch cell



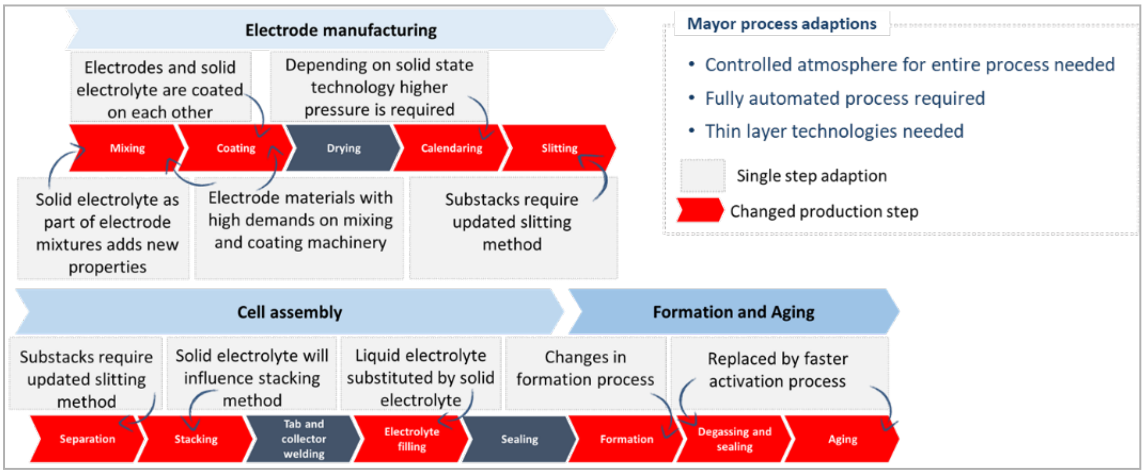
Source: P3 own representation.

Advancements in Li-ion cell production give an insight into cell costs and development paths. The Li-ion production costs can be reduced with various optimizations in machinery (i.e., increasing production speed) and process design. Novel production technologies could improve cell quality and contribute to the implementation of next generation materials (generation 3 and 4 in Figure 11). These new materials will have a major impact on costs of Li-ion batteries. Moreover, further price reduction with state-of-the-art cell technology is expected within the next years.

Manufacturing processes of the next generation cells will differ from state-of-the-art processes. For a long-term European battery manufacturing next generation technologies should be assessed and researched. Nonetheless, a market entry must happen before next generation technologies can be realized. Otherwise key learnings for production ramp-up and large-scale battery production will be missed.

All-solid-state belongs to the probable next generation technologies, as also stated above. Due to the substitution of liquid electrolyte with a solid-state one, several changes will be required in the production concept. An extract of the changes is summarized in Figure 13. As shown in the graph, almost every production step will require some changes and introduction of new advanced machinery for thin layers processing. Time reduction is also expected in the formation and aging process due to elimination of electrolyte filling step (Zarem et al., 2014; Schnell et al., 2018).

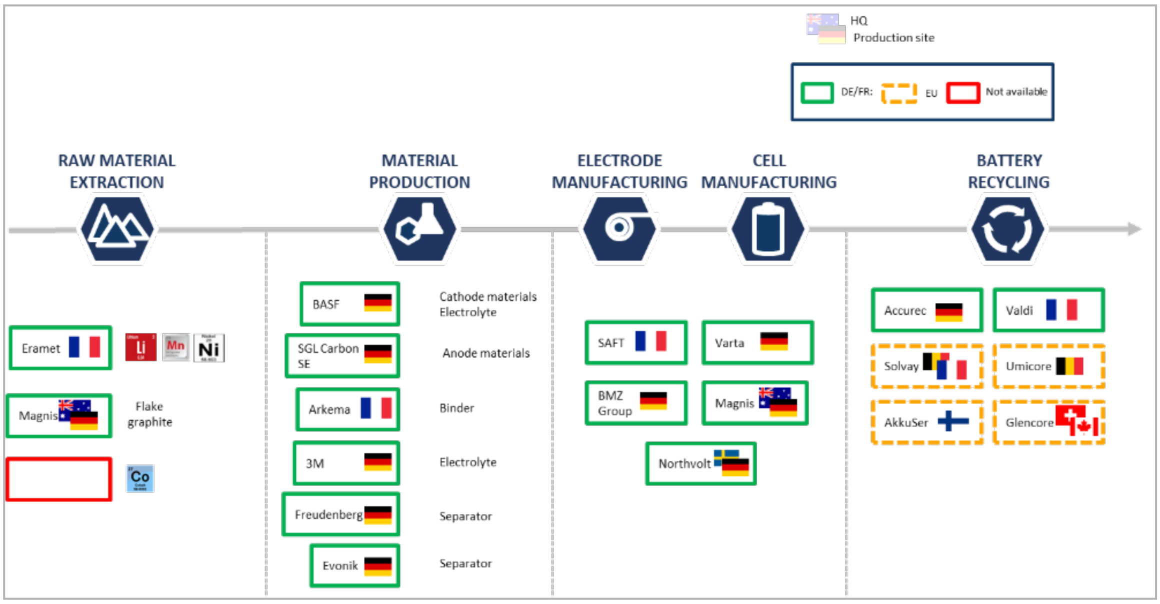
Figure 13: Required changes in the cell manufacturing process for the all-solid-state cell production



Source: P3 own representation.

After initial analysis of the challenges and success factors in every stage of value chain and short technology benchmarking, P3 evaluated the European companies (with focus on Germany and France), whose activities are related to Li-ion battery cell production/recycling. The overview of the selected companies is shown in Figure 14.

Figure 14: Overview of Li-ion cell market players (with a focus on Germany and France)

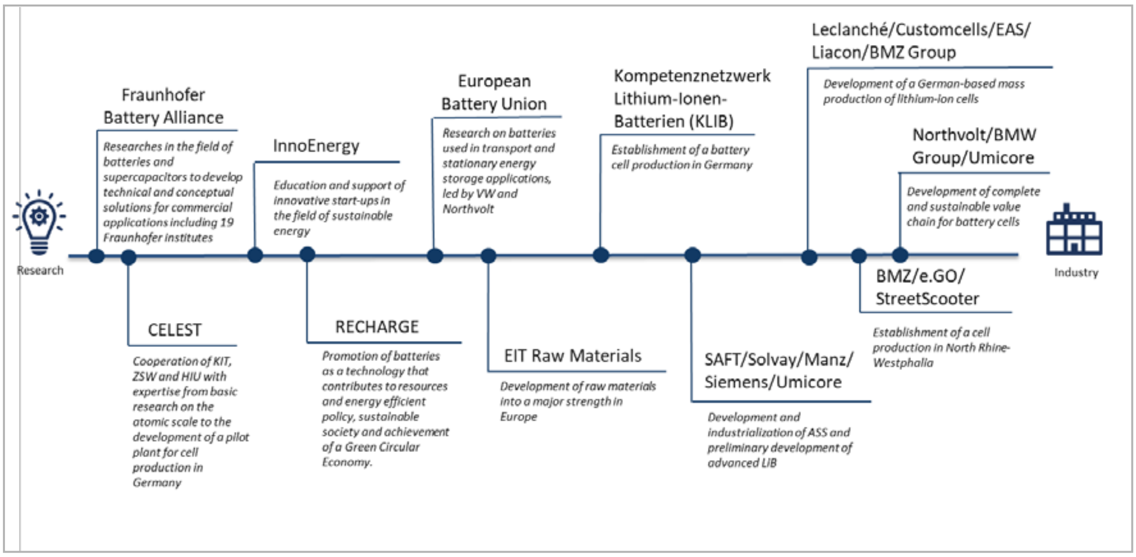


Source: P3 own representation.

According to P3 evaluation, these companies possess necessary know-how and have gained solid experience in the specific stages of the value chain. It can also be noted that there was no local supplier for cobalt found. For this German and French companies would need to establish cooperation with Scandinavian mining companies, such as Lead Edging Materials, Outotec and Terrafame. As for electrode and cell manufacturing, four companies have been identified, which either already have production facilities, like VARTA and Saft, or have announced the construction of GWh factories in the following years, like BMZ Group and Northvolt (in cooperation with VW). One the recycling side, two well-established companies, Accurec and Valdi, with annual capacities of 7000 and 20000 t, respectively, have strong ambitions for expansion of the business in Europe.

To achieve the high level of competitiveness with the Asian players, the formation of consortia is crucial. These consortia generally have either scientific or industrial focus and include several partners with experience along the value chain. The extract of the existing consortia is depicted in Figure 15.

Figure 15: Overview of the existing European consortia (extract)



Source: P3 own representation.

As follows from this figure, the main goal of the presented consortia is to offer novel materials, ensure the non-interruptive supply of raw materials and establish the mass production of battery cells. It is worth mentioning that several consortia are targeting Germany as a suitable location for new manufacturing sites. This is, on one hand, related to the short transportation paths to the German OEMs, and on the other hand, due to a strong financial support from the government and engagement of the companies towards environmentally friendly solutions.

Conclusion

The analysis of the Li-ion battery cell value chain has shown that the market is strongly dominated by the Asian players. According to P3 CO_2 compliance evaluation, the total battery market would grow up to 1200 GWh by 2025 with dominance of CATL in China and LG Chem in the remaining global market. The current study showed that the upstream integration of cell manufacturers in the raw material extraction and active material synthesis is important to enable a secure supply. Furthermore, the use of scarce materials must be further limited, and the use of hazardous materials must be strictly controlled. Cell manufacturing process requires fast production ramp-up aiming for low scrap rate and high quality at once. As for recycling, increase in the recycling rate and new CO_2-neutral methods will enhance the position of the European players, allowing them to offer such service to the leading cell manufacturers.
For the successful European entry in the cell manufacturing process several factors need to be evaluated. These from P3 point of view include:

- Approach to the market and enhancement of competition towards the existing players;
- secured raw materials supply in Europe at a reasonable price;
- further development of the education program to qualify the required competences;
- resolution of the environmental concerns with respect to the production of battery;
- determination of the main influence factors for the EU legislation to accelerate the development of new technologies.

Despite the dominance of Asian suppliers, the expected market demand leaves enough market chances for upcoming European cell projects. According to P3 evaluation, approximately ten gigafactories (à 18 GWh) will be necessary to close the currently expected gap of 180 GWh for the European market. Germany (and Europe in general) has excellent market access, a solid value chain and a highly talented workforce, which will put it in a favorable position to enter the Li-ion cell production landscape. The race to catch up will take at least five to eight years and cost ~10 billion euro. This time is scarce, but it is not too late yet.

References

ALABC The Advanced Lead-Acid Battery (2017): The Greatest Unknown Recycling Story.

Azevedo, M. et al. (2018): Lithium and Cobalt - a tale of two commodities. Available at: www.mckinsey.com/~media/mckinsey/industries/metals and mining/our insights/lithium and cobalt a tale of two commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx.

Benchmark Mineral Intelligence - Graphite price assessment (2018): Available at: www.benchmarkminerals.com/category/graphite/.

Berman, K. et al. (2018): BMO Capital Markets: The Lithium Ion Battery and the EV Market: The Science Behind What You Can't See. Available at: www.fullertreacymoney.com/system/data/files/PDFs/2018/February/22nd/BMO_Lithium_Ion_Battery_EV_Mkt_(20_Feb_2018).pdf.

Bernhart, W. (2019) Electromobilty: Key Raw Material Nickel is in short supply. Available at: www.rolandberger.com/en/Point-of-View/Electromobility-Key-raw-material-nickel-is-in-short-supply.html.

Bohlsen, M. (2019): Top 5 Nickel Producers And Other Smaller Producers To Consider, Seeking Alpha. Available at: https://seekingalpha.com/article/4246690-top-5-nickel-producers-smaller-producers-consider.

Boubou, W. (2019): Manganese: No Longer Just an Input on Steel, Technology Metals Edition Insight. Available at: www.theassay.com/technology-metals-edition-insight/manganese-no-longer-just-an-input-on-steel/.

Cobalt Institute (no date): Available at: www.cobaltinstitute.org/ores-containing-cobalt.html (Accessed: 20 August 2019).

Cobalt Statistics and Information (no date): Available at: www.usgs.gov/centers/nmic/cobalt-statistics-and-information. (Accessed: 10 December 2019)

Dante, R. C. (2016): 7 - Carbon materials, in Dante, R. C. B. T.-H. of F. M. and their A. (ed.). Boston: Woodhead Publishing, pp. 93–103. doi: https://doi.org/10.1016/B978-0-08-100619-1.00007-9.

Distribution of cobalt production worldwide in 2016, by company (2016): Available at: www.statista.com/statistics/692848/distribution-of-global-cobalt-production-by-producer/.

Elwert, T. et al. (2015): Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles, Recycling. doi: https://doi.org/10.3390/recycling1010025.

ERG Manganese Ore Concentrate (no date): Available at: www.eurasianresources.lu/en/pages/divisions-products/manganese-ore-concentrate (Accessed: 10 December 2019).

European Commision Report on Raw Materials for Battery Applications (2018): Brussels. Available at: https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf.

Fitch, B. and Yakovleva, M. (2017): Study of the Effect of Lithium Precursor Choice on Performance of Nickel-Rich NMC, Meeting Abstracts , MA2017-02(4), p. 324. Available at: http://ma.ecsdl.org/content/MA2017-02/4/324.abstract.

Friedrich, B., Träger, T. and Peters, L. (2017): Lithium-Ion Battery Recycling and Recent IME Activities, in AABC Europe. Available at: http://cii-resource.com/cet/AABE-03-17/Presentations/BATO/Friedrich_Bernd.pdf.

Gupta, U. (2019): Innovation boosts lithium-ion battery recycling rate to over 80%. Available at: www.pv-magazine.com/2019/03/25/innovation-boosts-lithium-ion-battery-recycling-rate-to-over-80/.

Here are the firms feeding China's battery revolution (no date): Available at: www.mining.com/web/firms-feeding-chinas-battery-revolution/ (Accessed: 9 September 2019).

International Lead Association (2014): Lead Recycling. Available at: www.ila-lead.org/UserFiles/File/ILA9927 FS_Recycling_V06.pdf.

Lithium and cobalt prices to remain under pressure as supply overtakes demand – report (2019): Available at: www.mining.com/lithium-and-cobalt-prices-to-remain-under-pressure-as-supply-overtakes-demand-report/.

Manganese – the third electric vehicle metal no one is talking about (2017): Available at: www.mining.com/web/manganese-the-third-electric-vehicle-metal-no-one-is-talking-about-it-heres-how-to-take-advantage/.

Mazumdar, R. (2019): MOIL Limited reports 9% increase in turnover. Available at: https://economictimes.indiatimes.com/industry/indl-goods/svs/steel/moil-limited-reports-9-increase-in-turnover/articleshow/68692031.cms.

Meiser, Eric; Michaelis, S.; Müller, D.; Haan, P.; Marz, P.; Eberlein, V.; Jakschik, S.; Schott, F.; Werner, C. (ed.) (2014): Roadmap Battery Production Equipment 2030. VDA Battery Production. Available at: http://battprod.vdma.org/documents/7411591/7483998/VDMA+Roadmap+Battery+Production+Equipment+2030/7acbecf6-0590-4754-984c-ecb378d2227b?version=1.0.

Noh, H.-J. et al. (2013): Comparison of the structural and electrochemical properties of layered Li [NixCoyMnz]O_2 (x = 1/3, 0.5, 0.6, 0.7, 0.8 and 0.85) cathode material for lithium-ion batteries, Journal of Power Sources, 233, pp. 121–130. doi: https://doi.org/10.1016/j.jpowsour.2013.01.063.

O'Brien, R. and Nickel, R. (2016): Battery-hungry world turns to South America's 'lithium triangle'. Available at: www.reuters.com/article/us-latam-lithium-idUSKCN0WH1BZ.

Raw materials scoreboard European innovation partnership on raw materials (no date): Available at: https://publications.europa.eu/en/publication-detail/-/publication/1ee65e21-9ac4-11e6-868c-01aa75ed71a1 (Accessed: 10 December 2019).

Reducing CO2 emissions from passenger cars (2009): Available at: https://ec.europa.eu/clima/policies/transport/vehicles/cars_en.

Sanderson, H. (2019): Huayou's profits tumble on cobalt prices collapse, Financial Times. London. Available at: www.ft.com/content/80f906d6-6a5d-11e9-80c7-60ee53e6681d.

Schlick, T.; Hertel, G.; Hagemann, B.; Maiser, E.; Kramer, M. (2011): Zukunftsfeld Elektromobilität Chancen und Herausforderungen für den deutschen Maschinenund Anlagenbau.

Schnell, J. et al. (2018): All-solid-state lithium-ion and lithium metal batteries – paving the way to large-scale production, Journal of Power Sources, 382, pp. 160–175. doi: https://doi.org/10.1016/j.jpowsour.2018.02.062.

Schröder, R., Aydemir, M. and Seliger, G. (2017): Comparatively Assessing different Shapes of Lithium-ion Battery Cells, Procedia Manufacturing, 8, pp. 104–111. doi: https://doi.org/10.1016/j.promfg.2017.02.013.

Shaun, V. (2017): Battery Anode Material. Available at: www.syrahresources.com.au/investors/downloads/523.

Siddharth Kara (2018): Is your phone tainted by the misery of the 35,000 children in Congo's mines? Available at: www.theguardian.com/global-development/2018/oct/12/phone-misery-children-congo-cobalt-mines-drc

South32 2018 Financial Results (2018): Available at: www.south32.net/docs/default-source/exchange-releases/2018-financial-results-presentation.pdf?sfvrsn=4af2d3af_2.

The Li-ion Battery Value Chain. New Economy Opportunities for Australia (2018).

Vale Annual Reports (no date): Available at: www.vale.com/EN/investors/information-market/quarterly-results/Pages/default.aspx (Accessed: 10 December 2019).

Weber, T. et al. (2016): NPE. Roadmap integrierte Zell- und Batterieproduktion Deutschland.

Why have Cobalt Prices crashed (2019): International Banker. Available at: https://internationalbanker.com/brokerage/why-have-cobalt-prices-crashed/.

Wiebelt, A. et al. (2009): Thermomanagement of Li-ion batteries, ATZ worldwide, 111(7), pp. 12–15. doi: https://doi.org/10.1007/BF03225083.

Xinhua (2019): China battery giant CATL achieves 304Wh/kg in new battery cells, China Daily. Available at: www.chinadaily.com.cn/a/201903/20/WS5c921ba0a3104842260b1a79.html.

Zarem, H. and Grape, U. (2014): Solid State Batteries for Gridscale Energy Storage. Available at: https://ww2.energy.ca.gov/2014publications/CEC-500-2014-101/CEC-500-2014-101.pdf.

Li-ion batteries are used in battery-powered vehicles, but also in power tools and consumer electronics. Due to the challenges posed by climate change and the increasing penalties for CO2 emissions, battery-powered electric vehicles are regarded as one of the solutions. Modern lithium-ion batteries are currently manufactured mainly by Asian manufacturers. However, the forecast demand for Li-ion batteries in Europe cannot be met by them. This gives the new European players the opportunity to enter the market and build local value chains.

ISSN 2509-2359