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Lithium ion battery value chain and related opportunities for Europe

Natalia Lebedeva
Franco Di Persio
Lois Boon-Brett



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Title: Lithium ion battery value chain and related opportunities for Europe

Abstract

Outline of automotive Li-ion battery value chain identifying current market volumes, leaders and status of the EU industry. The EU industry is far from being self-sufficient in all segments of the value chain. R&I investment are essential to respond to new opportunities presented by the EV market.

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Authors

Natalia Lebedeva

Franco Di Persio

Lois Boon-Brett

1 Introduction

Europe is on the cusp of an energy transformation - a transformation reducing energy demand, improving energy use efficiency and moving away from a high reliance on fossil fuels to an increased use of renewable energy sources for power and heat production and for transportation. The economic impacts of the energy transformation are important to consider as it should not hinder growth of the European economy - on the contrary Europe's ambition is to exploit its energy transformation as an opportunity for high value job creation and increased economic output, in addition to creating a more secure and resilient energy system with an ambitious climate policy.

Against this backdrop Europe has adopted the Energy Union Framework Strategy (COM (2015) 80 final) as part of its commitment to bring about the transition to a low-carbon, secure and competitive economy. The Energy Union Strategy is structured around five closely interrelated and mutually reinforcing dimensions addressing (i) energy supply security, (ii) a fully-integrated energy market, (iii) energy efficiency, (iv) decarbonising the economy and (v) research, innovation and competitiveness.

In September 2015 the Commission published a Communication on an Integrated Strategic Energy Technologies Plan (SET-Plan) [1]. This Communication defines a new European R&I Strategy for the coming years and as such is the first deliverable on which the fifth (v) dimension of the Energy Union will be built. It provides the overall framework for promoting strengthened cooperation in R&I between the European Commission, Member States and stakeholders such as research institutes, universities and industry (e.g. car manufacturers, chemical industry, mining industry, battery manufacturers, collectors and recycling industry), in order to step up the efforts to bring new and more efficient low-carbon technologies faster to the market and to deliver the energy transition in a cost-competitive way. Based on an integrated approach, going beyond technology silos, the Integrated SET-Plan identifies 10 R&I Key Actions to accelerate Europe's energy system transformation. The Integrated SET-Plan is supported by the EU Industrial policy (COM(2014) 14 final), which aims to stimulate growth and foster competitiveness in the manufacturing sector and the EU economy as a whole, by encouraging innovation through the support of actions related to innovation and research.

Key Action 7 of the Integrated SET-Plan (Become competitive in the global battery sector to drive e-mobility forward) is one of two Key Actions dedicated to the pursuit of more sustainable, efficient, low-emission transport systems, explicitly identified in the fifth dimension of the Energy Union. Strategic R&I targets and priorities up to 2030 have been set in Key Action 7 to strengthen European competences and capacities to become competitive in the global battery sector.

Similar as in other Key Actions these targets have been agreed in consultations between the European Commission and European experts from industry, academia and Member States. The targets are enshrined in a so-called "Declaration of Intent" [2]. Targets set in Key Action 7 aim at fostering research and innovation in the European battery sector to make EU industry more competitive. Unlike the other Key Actions, which cover exclusively research and innovation aspects, Action 7 explicitly considers competitiveness with respect to scaled-up manufacturing of higher performance batteries. Accordingly, targets set in Action 7 cover not only battery technology performance and cost parameters, they also cover battery manufacturing and recycling. Ratified by the national representatives from the SET-Plan countries and the Commission, these targets help define the expected actions, deliverables and time frames for a co-ordinated R&I&C agenda in the European battery sector.

Related to the competitiveness aspect of Key Action 7, a number of questions arise when considering ways for Europe to co-ordinate its R&I efforts and where to invest available research resources. For example, is it reasonable to assume that Europe could be competitive in all segments of the battery value chain or should European R&I&C investments focus on certain segments only? Which segment could offer the best return on investment, in terms of the overall return to the European economy?

Answering such strategic questions demands judicious consideration of the current status and market outlook for electric vehicle batteries, but also for batteries used in other applications, as well as of the position and competitive edge enjoyed by the various global economies active in this sector. The European Commission's Joint Research Centre (JRC) has prepared the current report for this purpose. This report outlines the Li-ion battery value chain, and indicates for each segment current market volumes and leaders as well as the status of the EU industry. This report does not provide an exhaustive economic assessment with a detailed entry barrier analysis (e.g. evaluation of market centralization rate, capital requirements, human resources, consumer purchase behaviour) for the return of the investments in terms of productivity and global competitiveness. Nevertheless the information can be used to help underpin decisions regarding where R&I investments having the biggest impact in terms of boosting European competitiveness can be made. In this context the global dimension of the battery sector should be considered bearing in mind the competition from the US and Asia, delocalization of manufacturing capacity and potential dispersion of the knowledge base which has the tendency to move where production sites are located [3].

The scope of this report largely matches that of the Key Action 7 Declaration of Intent which considers lithium ion and post lithium ion chemistries the most promising and relevant chemistries for electrochemical energy storage in the time frame up to 2030.

Contrary to the Declaration of Intent, this report considers only automotive traction battery applications for which relevant data on the current market situation, position of the main global players and future market outlook has been sourced. Doing so does not preclude the need or importance of battery R&I to advance the European position in other applications such as for stationary energy storage, where European competitiveness can be further improved and enhanced. Indeed development of affordable and integrated energy storage solutions to accelerate full integration of storage devices (including electrochemical) into a low-carbon energy system is explicitly mentioned, in addition to electro-mobility, in the Accelerating Clean Energy Innovation Communication (COM(2016) 763). As such it is one of the priority areas where future EU funding under Horizon 2020 will be focused. Notwithstanding this, competitiveness of the European battery sector for applications other than e-mobility is beyond the scope of this report.

2 Automotive lithium-ion battery value chain

Figure 1 illustrates the value chain for automotive Li-ion batteries*. The value chain is divided into 6 segments spanning the spectrum from raw material mining to battery recycling. Mining and chemical industries provide the myriad of raw and processed materials used in the production of the various cell components including the anode, cathode, electrolyte and separator. These components are then assembled in individual cells. Some materials are produced and used exclusively in Li-ion cell production while others can be used for other purposes. While the majority of the produced Li-ion cells are assembled for use in portable electronic devices, a fast growing share is destined for use in battery packs for electric vehicles. When batteries reach the end of life in their first application they can be recycled or alternatively employed in a second use application (e.g. for stationary energy storage).

In the following section each battery value chain segment is discussed highlighting key figures and relevant industry revenues. Revenues provided for cell component, cell and pack manufacturing refer to the global Li-ion battery industry, whereas for other value chain segments the relevant EU industry revenue is provided. While revenues specific to the Li-ion traction battery industry are still marginal, its Compound Annual Growth Rate (CAGR) for the upcoming years is quite significant.

Where possible, key global and European players have been identified for each segment. It is worth noting that activities of some companies cover different segments of the value chain. For instance some cell manufacturers also manufacture cell components especially for the cathode, while other players active in the recycling sector are also active in the materials processing segment. Furthermore, the US electric vehicle manufacturer Tesla, demonstrates an approach to also lay claim on the manufacturing of cells and battery packs.

The data presented for all segments was, at the time of publication of this report, the most up-to-date representative data retrievable by the authors. However the extremely dynamic nature of the market being considered is such that the absolute and relative magnitude of the data reported is changing rapidly.

* In this report, the term "*Automotive batteries*" refers to batteries on-board a vehicle used for traction and is used as a synonym of "*industrial batteries*" as defined in the Battery Directive 2006/66/EU.




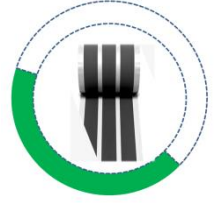

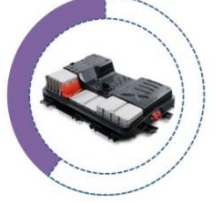
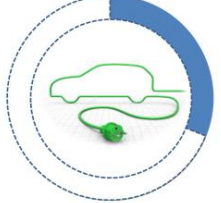

						
Most Relevant Statistics	51 %	43 %	88 %	40 %	31 %	50 %
	Democratic Republic of Congo's share of global cobalt production [4] - a critical material for Li-ion technology	Cathode revenue as share of cell components market [5]	Asian share of Li-ion cell manufacturing market [6]	Share of pack assembly cost over the total battery pack cost [7]	Automotive share of Li-ion cell market in volume (MWh) [8]	Recycling efficiency for Li-ion batteries set in the Battery Directive [9]
Revenues	EU Mining and quarrying industry revenues: B\$ 19 [1] EU Chemical industry Revenues: B\$ 28 [1]	Global Li-ion cell components Industry revenues: B\$ 7 [5]	Global Li-ion cell manufacturing revenues: B\$ 16.7 [5]	Global automotive battery pack manufacturing revenues: B\$ 22 [5]	EU Automotive industry Revenues: B\$ 900 [10]. 20% of worldwide [11]	EU Waste collection & Recycling Industry Revenues: B\$ 150 [10]. 75% of worldwide [12]

Figure 1: Automotive lithium-ion battery value chain (data from 2015).

3 Value chain segments – status, recent developments and opportunities

3.1 Raw and processed material

A wide range of elements is used in Li-ion battery cells including lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), aluminium (Al), copper (Cu), silicon (Si), tin (Sn), titanium (Ti) and carbon (C) in a variety of forms, e.g. natural graphite. These elements are harvested from raw materials mined from the earth's crust or recovered from surface water.

Some of these materials have a high economic importance while at the same time have a high supply-risk and as such are termed "critical raw materials (CRMs)" [4], [13], [14]. The European Commission publishes a list of CRMs which is reviewed and updated every three years. As explained in the EC Communication [4]: "The purpose of the list is to contribute to the implementation of the EU industrial policy and to ensure that European industrial competitiveness is strengthened through actions in other policy areas. This should increase the overall competitiveness of the EU economy, in line with the Commission's aspiration of raising industry's contribution to GDP to as much as 20% by 2020. It should also help to incentivise the European production of critical raw materials and facilitate the launching of new mining activities. The list is also being used to help prioritise needs and actions. For example, it serves as a supporting element when negotiating trade agreements, challenging trade distortion measures or promoting research and innovation" [4]. A new CRM list is expected to be published in 2017.

Among the materials used in Li-ion cells, three are listed as CRMs namely, cobalt, natural graphite and silicon (metal) [4]. Uses, current supply and forecasted availability of each of these materials are reported in this section. Similar information is also reported for lithium even though it is not considered a CRM. However for obvious reasons availability and supply of lithium has a high impact on the Li-ion battery industry. Table 1 lists the main producers, main European import sources, the substitutability index[†] and the end of life recycling input rate[‡] for each CRM and for lithium.

[†] 'Substitutability index' is a measure of the difficulty in substituting the material, scored and weighted across all applications. Values are between 0 and 1, with 1 being the least substitutable.

[‡] 'End-of-life recycling input rate' measures the proportion of metal and metal products that are produced from end-of-life scrap and other metal-bearing low grade residues in end-of-life scrap worldwide.

Table 1: Main producers, main source of import into EU, substitutability index and recycling rate of cobalt, natural graphite, silicon metal and lithium. [4, 15-18]

Raw material	Main producers (2014-2015)	Main sources of imports into the EU (mainly 2012)	Substitutability index	End-of-life recycling input rate
Critical raw materials used in Li-ion batteries				
Cobalt	Democratic Republic of Congo: 51 % China: 6 % Russia: 5 % Canada: 5 % Australia: 5 %	Russia: 96 % (cobalt ores and concentrates) USA: 3 % (cobalt ores and concentrates)	0.71	16 %
Natural graphite	China: 66 % India: 14 % Brazil: 7 %	China: 57 % Brazil: 15 % Norway: 9 %	0.72	0 %
Silicon metal	China: 68 % Russia: 8 % USA: 5 % Norway: 4 %	Norway: 38 % Brazil: 24 % China: 8 % Russia: 7 %	0.81	0 %
Non-critical raw material used in Li-ion batteries				
Lithium	Australia: 41 % Chile: 36 % Argentina: 12 % China: 7 %		n.a.	n.a.

3.1.1 Cobalt

Cobalt is used for a number of industrial applications such as in batteries, superalloys, hard materials – carbides, diamond tooling, pigments, catalysts, magnets etc. [14]. Use in batteries has the biggest share among these applications, equivalent to around 37% [4]. In Li-ion batteries, cobalt is a component in several widely used cathode active materials.

Identified world terrestrial cobalt resources are about 25 million tons (for definitions of resources and reserves please see [19]). More than 120 million tons of cobalt resources have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans [15]. At the beginning of 2016 world reserves were estimated to be 7,1 million tons and total world production of cobalt in 2015 amounted to 0,124 million tons [15]. Just as in previous years, production of cobalt in 2014-2015 was highly concentrated. Democratic Republic of Congo (DRC) continued to be the world's leading source of mined cobalt, supplying 51 % of the cobalt market volume (see Table 1) [15], with China, Russia, Canada and Australia each having a much lower share (see Table 1) [15]. In addition to the high concentration of cobalt production, there are further concerns regarding the social aspects of cobalt mining in the DRC such as forced and child labour and unsafe working conditions [20].

The vast majority of cobalt import into the EU comes from Russia (96 %). Cobalt has a low substitutability (substitutability index for all applications is 0.71 and for batteries it is 0.8) and a reasonably low end-of-life recycling input rate for all applications of 16 % [4].

The forecasted market balance for cobalt, covering all applications until 2020, indicates a small surplus while the market is forecasted to be balanced in 2020 (i.e. supply matching demand within 1 %) [13]. Longer term projections for penetration of electric vehicles up to 2050 show that the cumulative demand for cobalt would require all the resources known today, even considering its relatively high recycling rate in the battery sector. However this estimation is based on the assumption that NMC technology continues to be widely used up to 2050 [21], which is unlikely as gradual introduction of other cobalt-free chemistries is expected in this time frame (see Future cell chemistries section).

3.1.2 Natural graphite

Natural graphite is used in a number of industrial applications: electrodes, refractories, lubricants, foundries and in batteries as anode active material [13]. Application in batteries has a relatively low share of 4 % [13].

World's inferred resources exceed 800 million tons of recoverable graphite, reserves of natural graphite are estimated to be 230 million tons and world mine production in 2015

amounted to ca. 1,2 million tons [16]. Production of natural graphite is highly concentrated with China producing 66 %, India 14 % and Brazil 7 % of the natural graphite market volume (see Table 1) [16]. The majority of natural graphite import into the EU comes from China (57 %) followed by Brazil (15 %) and Norway (9 %). In some applications natural graphite has a (very) low substitutability (substitutability index for all applications is 0.72), but in batteries substitution of natural graphite by other materials is feasible (substitutability index is 0.3) [13]. The end-of-life recycling input rate of natural graphite is 0 %.

It is forecasted that the natural graphite market in 2020 will experience a large surplus of production (i.e. supply exceeding demand by more than 10 %) [13].

3.1.3 Silicon metal

Silicon metal is widely used in the chemical, pigments, metallurgy and electronics industries [13]. Silicon metal and silicon alloys are also emerging as anode active materials for Li-ion battery cells, but at present their share is negligible compared to other applications.

World resources for making silicon metal and alloys are abundant and adequate to supply world requirements for many decades. The source of silicon is silica in various natural forms, such as quartzite. The reserves in most major producing countries are also ample in relation to demand, but no quantitative estimates are available [17]. World's production of silicon metal in 2015 amounted to 8,100 tons and was highly concentrated with China producing 68 %, Russia 8 %, USA 5 % and Norway 4 % of the silicon metal market volume (see Table 1) [17]. The majority of silicon metal imported into the EU comes from Norway (38 %) followed by Brazil (24 %), China (8 %) and Russia (7 %). Silicon metal has a (very) low substitutability having a substitutability index of 0.81 for all applications [13]. The end-of-life recycling input rate of silicon metal is 0 % [13].

It is forecasted that the silicon metal market in 2020 will be balanced (i.e. supply matching demand within 1 %) [13].

3.1.4 Lithium

Although lithium is not classified as a critical raw material it is an important element in lithium-ion battery technologies. Lithium has a relatively high average abundance in the earth's crust of 17 ppm [22], making it the 27th most abundant element in the lithosphere. For various reasons, outlined in [22], exact data on global resources, reserves and production of lithium is not available, figures cited below are best estimates available. A comprehensive overview of lithium resources, reserves, production volume and producers is given in [22]. Global resources and reserves are estimated to be 39.5-

45.2 million tons and 12.2-14 million tons Li metal equivalent[§] (LME), respectively [18, 21, 22]. Geographical distribution of resources and reserves is shown in Figure 2.

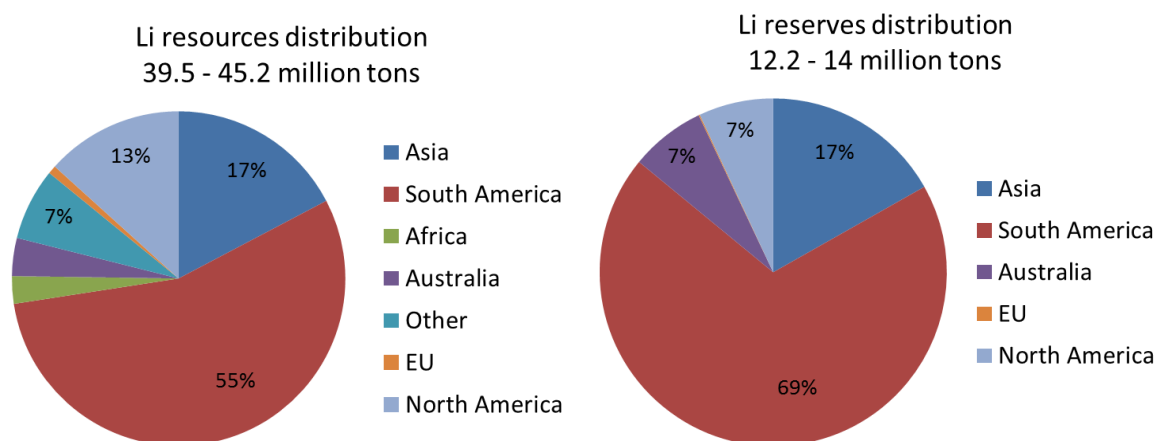


Figure 2: Geographical distribution of Li resources and reserves. Source: [22]

Major Li resources and reserves - nearly 25 million tons Li metal equivalent (LME) and 8.5 million tons LME, respectively - are identified in South America, notably in Argentina, Chile, Bolivia and Brazil, where 55% of the global resources and 69% of the global reserves are located [22]. China possesses the biggest part of Li resources and reserves found in Asia (ca. 5.3 million tons LME and 2.1 million tons LME respectively) corresponding to around 12% of the global resources and nearly 17% of the global reserves [22]. EU's share of the global Li resources and reserves is limited - slightly less than 0.4 million tons LME and 0.013 million tons LME, respectively [22]. However, unique deposits of jadarite - lithium boron silicate - were discovered in 2004 in Serbia. So far only one such deposit is known, its resource is 1.5 million tons LME, which corresponds to ca. 2% of the global resources [22]. Significant Li resources and reserves are identified in North America - nearly 6 million tons LME and 0.8 million tons LME, respectively. More than half of these is located in the USA, corresponding to nearly 8% of the global resources and 5 % of the global reserves [22].

Global supply of lithium has been historically dominated by hard-rock mineral sources, however development of large-scale lithium brine operations in South America commenced in the early 1980's. The actual global supply market for lithium products is

[§] Lithium is found in nature in a number of mineral forms and compounds with different Li metal content. To account for this, numbers for Li resources and reserves are given in literature recalculated to Li metal equivalent, i.e. amount of Li contained in ores, brines etc.

around 200,000 tons of lithium carbonate equivalent (LCE) (1 kg LCE = 0.1895 kg Li), with almost 83% of it being sourced from four major producers: Albemarle (USA), SQM (Chile), FMC (USA) and Sichuan Tianqi (China) with main fields located in Chile, Australia, Argentina and China (see Table 1) [23].

In 2015 Li-ion batteries consumed around 40 % of the global LCE production, of which 14% was used for electric vehicle battery packs. Projection for 2025 shows that electrical vehicle demand alone will utilise 200,000 tons of LCE, which equates to the total current global LCE supply [23].

Therefore the known lithium reserves are sufficient to cope with this foreseen increase in demand even without recovery of lithium from the recycling of Li-ion batteries. Today the recovery of lithium from batteries is technically feasible, but is still not economically viable. However, foreseen long term lithium price development or new practices may make lithium recovery more viable in the future [21].

3.2 Cell components manufacturing

3.2.1 Cathode materials

Aluminium foil is used as a current collector for cathodes in Li-ion cells. Market leaders in aluminium foil production for battery applications are Sumitomo Light Metal Industries (JP) and Nippon Foil Mfg. (JP) [24].

Complex transition metal oxides and phosphates are currently the main cathode active materials used in Li-ion battery cells. These include: Lithium Cobalt Oxide (LCO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminium Oxide (NCA), Lithium Manganese Oxide (LMO) and Lithium Iron Phosphate (LFP). With the exception of LCO, all these materials are currently used in automotive Li-ion battery cells [25],[26]. The total market demand for cathode materials for all applications of Li-ion batteries was approximately 140,000 tons in 2015; revenues generated were B\$ 3 and the market showed a sustained growth with compound annual growth rate (CAGR) amounting to 16% between 2005 and 2015 [27] (see Figure 3). It is estimated that approximately 25% of the total global demand of the cathode active materials or ca. 5,000 tons was used in Li-ion batteries for HEVs, PHEVs and EVs.

Cathode active materials for LIB in Tons, 2000-2015 (Demand)

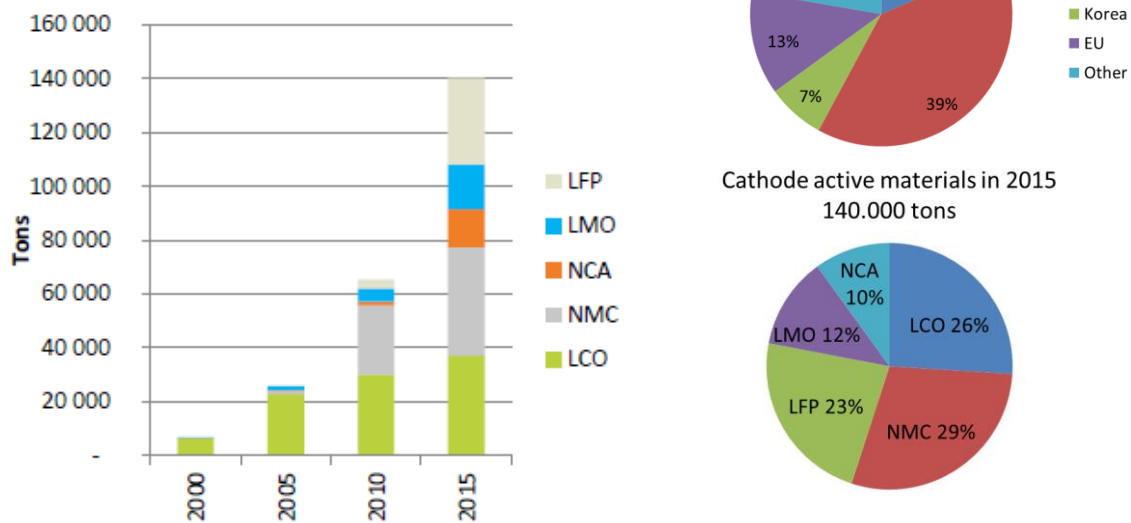


Figure 3: Left – Development of the cathode active materials market in 2000-2015 (Used with permission from Avicenne Energy [5]). Right – demand division per material type (Used with permission from Avicenne Energy [5]) and regional distribution of the manufacturers (according to the location of the headquarters) in 2015 (based on data from [5]).

Production of cathode active materials is dominated by Asia, with China manufacturing ca. 39 % (by weight) of the total amount of cathode materials in 2015, Japan – ca. 19 % and South Korea – ca. 7 % (see Figure 3).

Suppliers from the EU – Umicore** (BE) and Johnson Matthey (UK) – together produced ca. 13 % (by weight) of the total amount of cathode materials or ca. 17,700 tons in 2015. Umicore produced ca. 5,550 tons of LCO (note however that LCO is less relevant for automotive applications) and ca. 9,600 tons of NMC and Johnson Matthey (UK) produced ca. 2,560 tons of LFP.

The cathode materials market remains very dynamic and is currently seeing "de-concentration" with more and more companies entering the market and providing a share of the global supply. For example, in 2011 61% of the global market for cathode materials was shared by only three (3) dominating suppliers, namely Umicore (BE) with 32%, Nichia (JP) with 24% and Toda Kogyo (JP) with 5% [24]. In 2014 six (6) main suppliers together had a market share of ca. 45% with Umicore (BE) having 11%, Reshine (CN) 8%, L&F (KR) 8%, ShanShanTech (CN) 7%, Nichia (JP) 7% and Sumitomo

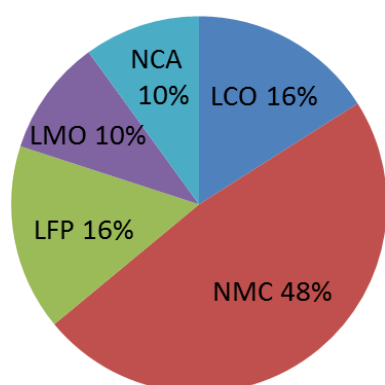
** Umicore is considered an EU-based company in this report, despite the fact that the actual production of the cathode active materials takes place at the Umicore's facility in South Korea.

(JP) 5% [27]. In just one year, each of these main producers further increased their production volume and together they held a 52% share of the total market in 2015 [5].

Companies such as BASF (DE), Dow (US), 3M (US), DuPont (US), Mitsubishi (JP) and LG Chem (KR) have recently shown interest in this market but do not play a significant role in the global supply of the cathode active materials yet [27].

Based on a number of assumptions [5], the market for cathode active materials is expected to grow from ca. 140,000 tons in 2015 to ca. 400,000 tons in 2025 with the relative fraction per material changing as shown in Figure 4. The highest growth rate is expected for NMC (almost 5 times), NCA (ca. 3 times) and LMO (2.4 times), and EU suppliers have the opportunity to increase their supply of NMC. Production of NCA material, currently dominated by Japan, may also present an opportunity for existing/new EU manufacturers.

Cathode active materials in 2025
400.000 tons



	2015		2025		Expected growth times
	%	ktons	%	ktons	
LCO	26	37	16	64	1.7
NMC	29	40	48	192	4.8
LFP	23	32	16	64	2.0
LMO	12	17	10	40	2.4
NCA	10	14	10	40	2.9
Total	100	140	100	400	2.9

Figure 4. Expected market volume per material type in 2025 (left) (Used with permission from Avicenne Energy) [5] and as compared to 2015 (right) (based on data from [5]).

However, the potential of technical breakthrough that leads to use of different cathode materials/chemistry, intensive competition and government policy interference will continue to affect global cathode manufacturing sector [23].

The quality of the cathode material impacts the overall performance of the cell. Quality control starts in the raw material production stage and this is particularly true for cathode manufacturing. For this reason many of the major battery cell manufacturers such as Panasonic (JP), LG Chem (KR), BYD (CN) have chosen to develop their own in-house cathode materials production capacity [23].

3.2.2 Anode materials

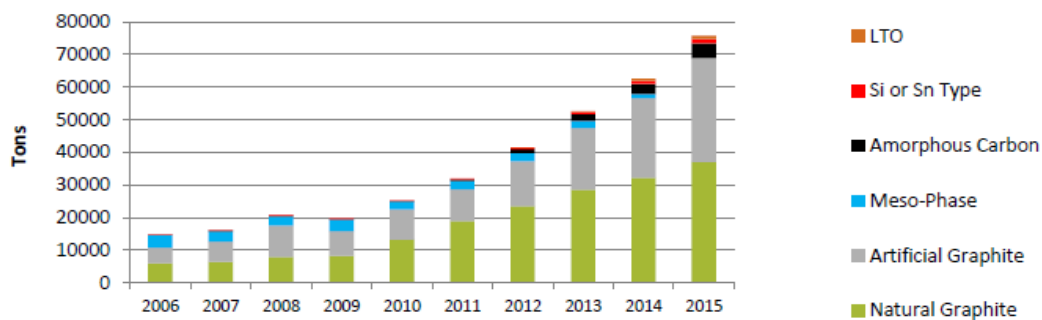
Copper foil is used as a current collector for anodes in Li-ion cells. Market leaders in copper foil production for battery applications are Furukawa Electric (JP), Nippon Foil Mfg. (JP) and Nippon Denkai (JP) [24].

Various carbonaceous materials such as natural and artificial graphite, meso-phase and amorphous carbon and more recently tin and silicon oxides and alloys, as well as Lithium Titanium Oxide (LTO) are used as anode active materials [5, 27].

The total market for anode materials for all applications of Li-ion batteries exceeded 76,000 tons in 2015; revenues generated were B\$ 1 and the compound annual growth rate (CAGR) amounted to 14% in the period from 2005 to 2015 [5].

Approximately 40% of the total global demand of the anode active materials (ca. 30,400 tons) was used in Li-ion batteries for HEVs, PHEVs and BEVs [5].

Development of the market in 2006-2015 and the division of the market per type of anode material is shown in Figure 5. It can be seen that the largest share of the market – ca. 91% - is taken by graphite and is almost equally divided between natural graphite and artificial graphite, 49 % and 42% (by weight), respectively, of all anode active materials for all Li-ion battery applications [5].



Anode active materials in 2015:
75 000 Tons

Regional distribution of the top-12 manufacturers of natural and artificial graphite anode materials in 2015

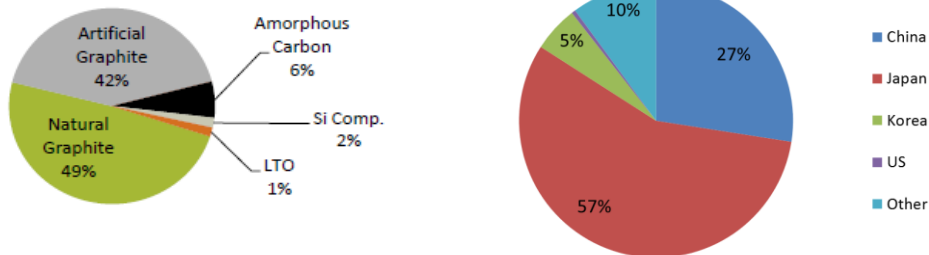


Figure 5: Development of the anode active materials market in 2006-2015, market division per material type (Used with permission from Avicenne Energy [5]) and regional distribution of the top-12 manufacturers of natural and artificial graphite anode materials in 2015 (based on data from [5]).

Historically the production of anode active materials has been dominated by Japan and China (see Figure 5) [5, 24, 25]. In 2011 three (3) producers together had a market share of 65 % with Hitachi Chemicals (JP) having a share of 34 %, Nippon Carbon (JP) – 19% and BTR Energy (CN) – 12% [24], [25]. In 2015, these 3 companies remain the leaders in the market of anode active materials supplying 61% of the market [5]. Hitachi Chemicals (JP) remains the largest producer (31% of the market) with BTR Energy (CN) following in second place (19%) and Nippon Carbon (JP) in third place (7%). Other producers of anode active materials include Mitsubishi Chemical (JP), LS Mtron Carbonics (KR), ShanshanTech (CN), Tokai Carbon (JP) [5].

EU-based companies such as SGL (DE), Imerys (CH) and Heraeus (DE), as well as 3M (US), DuPont (US), Dow (US), Dow Corning (US), Envia (US), ShinEtsu (JP) have recently shown interest in the anode active materials market for Li-ion batteries but currently do not play any significant role in the global supply.

The market for anode active materials is expected to grow from 76,000 to more than 250,000 tons in 2025. The expected distribution of the market among various anode active materials in 2025 is shown in Figure 6. The forecast is that the share of artificial graphite will increase to 52%, that of natural graphite decrease to 24% and the share of other anode active materials will grow to 24% [5].

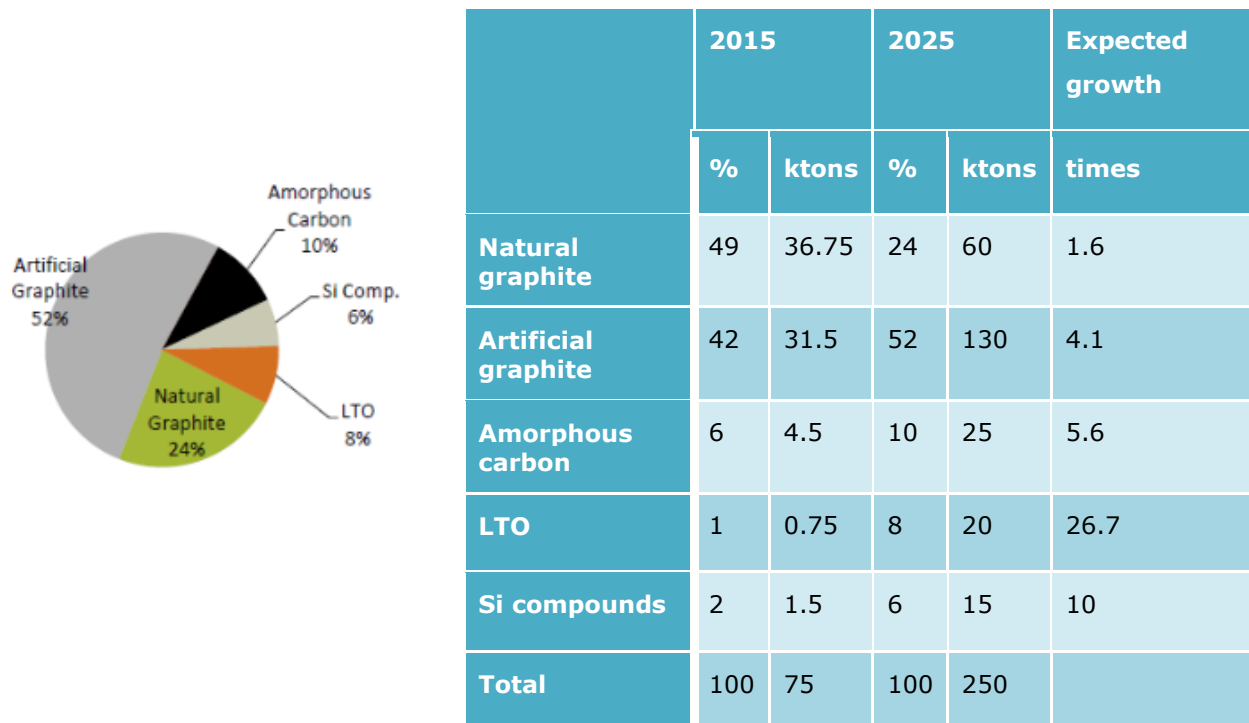


Figure 6: Forecast market division per anode active material type in 2025 (left) (Used with permission from Avicenne Energy [5]), and as compared to 2015 (right) (based on data from [5]).

3.2.3 Electrolytes

The global market for electrolytes for all applications of Li-ion batteries was slightly bigger than 62,000 tons in 2015; revenues generated were B\$ 0.9 and the compound annual growth rate (CAGR) in 2005 to 2015 amounted to 20% [5].

The market for electrolytes for HEV, PHEV and BEV batteries has experienced a rapid growth in the period from 2010 to 2015, with electrolyte demand for these applications increasing from ca. 200 tons in 2010 to ca. 20,500 tons in 2015 (or ca. 33 % of the total market volume for Li-ion batteries) [5, 28].

Similar to cathode and anode active materials, the production of electrolytes for Li-ion batteries is dominated by the Asian suppliers, with China currently producing close to 60 % (by weight) of the total market, Japan – 18 % and Korea – 14 % (see Figure 7). Soulbrain - a producer with headquarters in the US and production facility in Korea – has supplied 7 % of the market in 2015. The EU-based electrolyte producer – BASF (DE) – has supplied ca. 200 tons of electrolyte or ca. 0.4 % of the total market volume in 2014, but decreased the supply significantly in 2015 [5, 28].

LIB electrolyte market, Tons,
CAGR 2005/2015: +25%

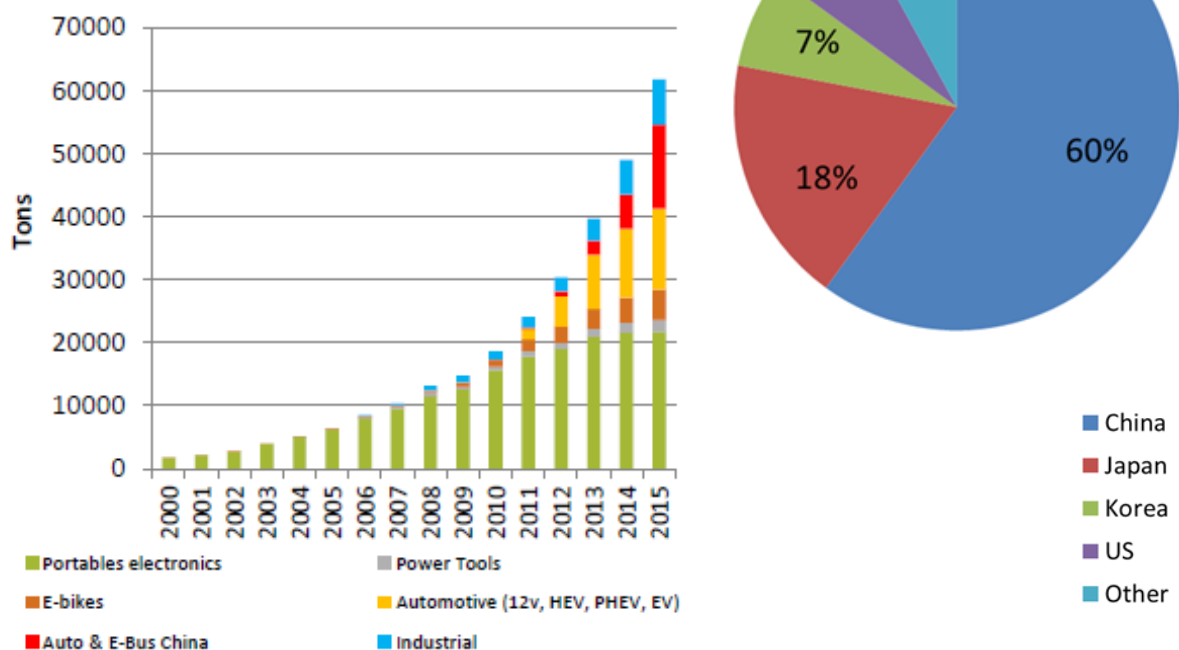


Figure 7: Left – Development of the electrolyte market in 2000-2015 (Used with permission from Avicenne Energy [5]) and right – Regional distribution of the electrolyte producers in 2015 (based on data from [5]).

The competition in the market is very intense, with Chinese companies expanding their production volume quickly and others slowing their growth or even experiencing a decline [5, 28]. One of the quickest growing Chinese electrolyte producers, CapChem, has more than doubled its share on the market from ca. 3,500 tons in 2013 to 8,600 tons in 2015 to become the global market leader with a 14 % share of the total electrolyte market. Zhangjiagang Guotai-Huarong (GTHR) (CN) has also increased its production from ca. 3,500 tons in 2011 to 8,000 tons in 2015 becoming the second biggest electrolyte supplier with a 13 % share of the total electrolyte market in 2015. Conversely, Korean (e.g. Panax-Etec) and mainly Japanese (e.g. Mitsui Chemicals and Ube) electrolyte producers are currently experiencing a decrease of their market share [5, 27].

New entrants on the global market of electrolytes for Li-ion batteries are companies such as LG Chem (KR), DuPont (US) and Daikin (JP) [5, 28].

Worldwide there is currently a significant overcapacity for electrolyte production for Li-ion batteries (see Figure 8) [5]. Less than half of the available production capacity is currently being utilised in Japan and Korea and in the US and Europe only 5% and 1%, respectively.

The Demand					
	Japan	Korea	China	US	Europe
	14 000 Tons 4000 Tons import	22 000 Tons 12000 Tons import	25 000 Tons >15 000 tons export	<1000Tons	< 500 Tons Almost100% import
The Offer					
	Japan	Korea	China	US	Europe
Production	12 000	9 000	40 000	1100	100
Capacity	30 000	20 000	60 000	22 000	11 000
Prod. ratio	40%	45%	66%	5%	1%

Figure 8: World-wide demand and offer of electrolytes for Li-ion batteries (Used with permission from Avicenne Energy [5].)

Nevertheless, there may be opportunities in formulation and production of new advanced electrolytes, e.g. for high-voltage Li-ion cells, where advanced (likely fluorinated) additives and solvents will be required [5]. Given this dynamic market climate and taking into account the expected market growth, there may be business opportunities present for EU-based producers.

The market for electrolytes is expected to grow from the current 62,000 tons to more than 235,000 tons in 2025, with the automotive share increasing from current ca. 33% to ca. 50% of the market, see Figure 9 [5].

From 62 000 Tons in 2015 to >235 000 Tons in 2025 CAGR: +13%

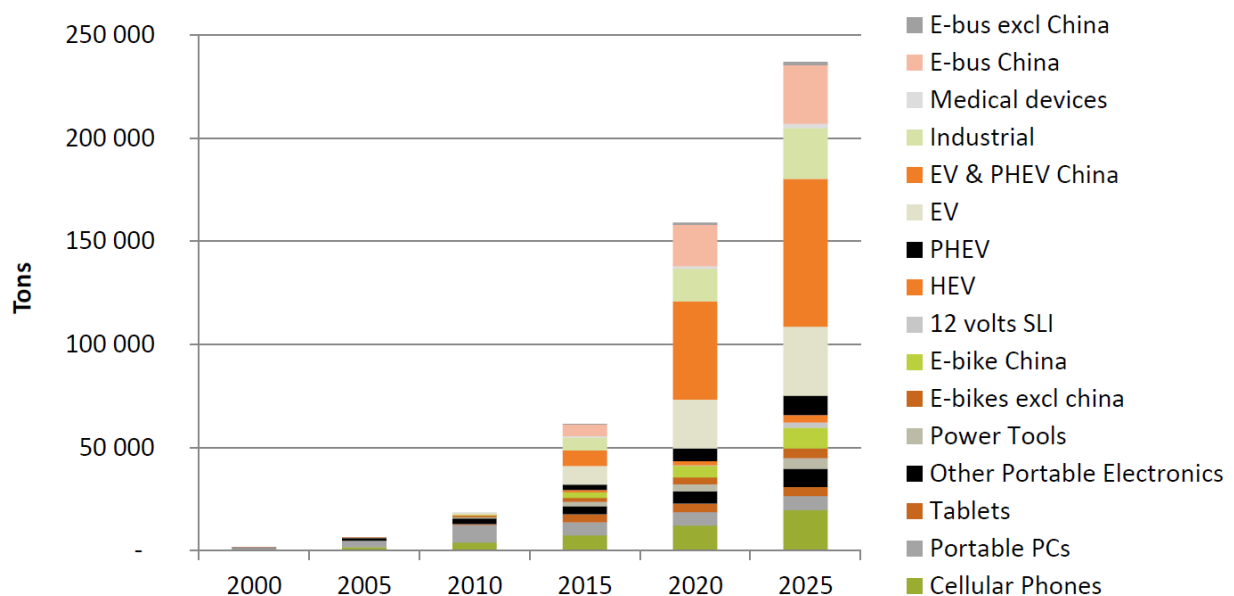


Figure 9: Electrolyte market forecast till 2025 (Used with permission from Avicenne Energy [5].)

3.2.4 Separators

The total market for separators for all applications of Li-ion batteries was approximately 900 Mm² in 2015; revenues generated were B\$ 1.1 and the compound annual growth rate (CAGR) amounted to 15% in the period between 2005 and 2015 [5]. Approximately 30% of the global separator market volume or ca. 300 Mm² is supplied for production of automotive Li-ion battery cells [5].

As for cathode and anode active materials and electrolytes, the market of separators for Li-ion batteries is dominated by Asia, with Japan's current market share of 48 % (by product surface area, Mm²) of the total market supply, China – 17 % and Korea – 10 %

(see Figure 10). Market leaders are Asahi Kasei (JP), Toray (JP) and SK (KR). The separator market position of the US is also strong with Celgard having a market share of 9% and Entek of 3% in 2015 [5].

Companies such as DuPont (US), Dow (US), LG Chem (KR), Teijin (JP) and Mitsubishi (JP) have recently shown interest in the separator materials market for Li-ion batteries but currently do not play any significant role in the global supply. EU-based Evonik (DE) is among the new entrants on the market of separator materials [5]. Litarion (DE) has manufacturing capacity to produce electrodes and ceramic separators for lithium-ion battery cells, but the actual production volume for 2015 is unknown [29].

Separator market in volume (Mm²) by suppliers

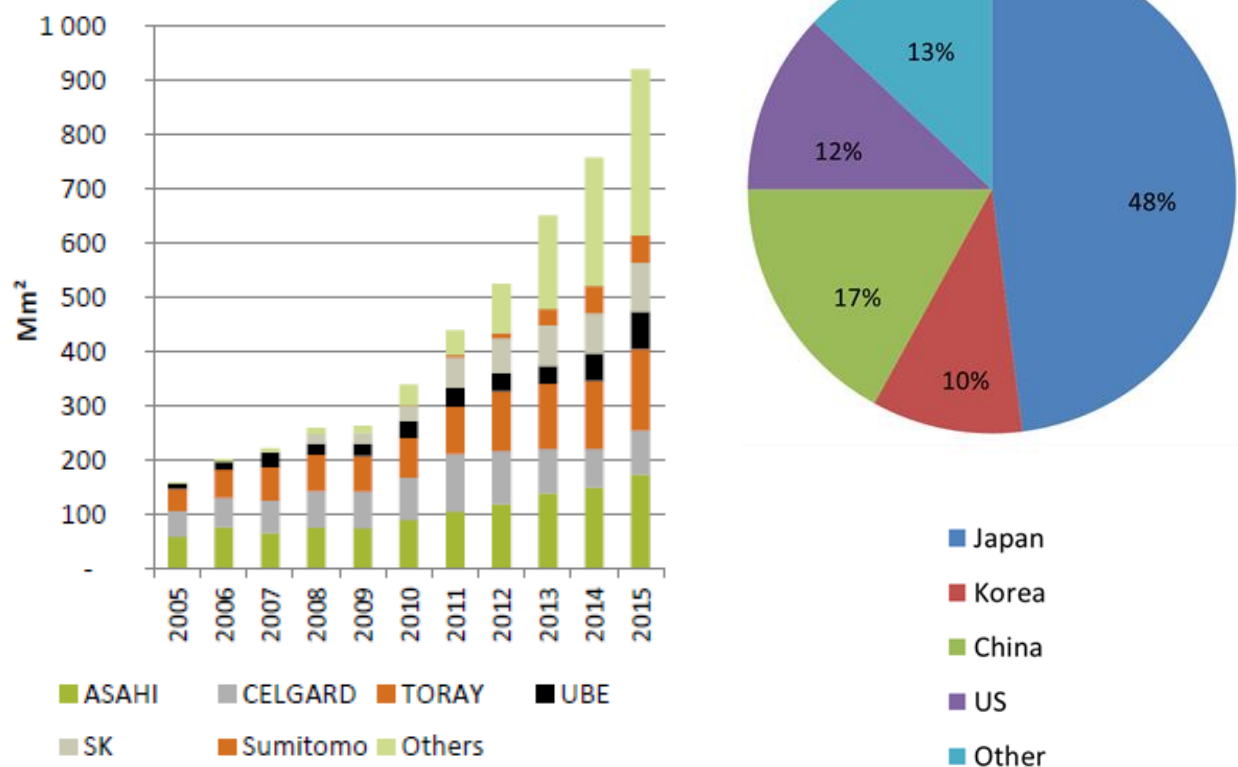


Figure 10: Left – Development of the separator market in 2005-2015 [5] (Used with permission from Avicenne Energy [5]) and right – Regional distribution of the separator producers in 2015 (based on data from [5]).

It is expected that the separator market for Li-ion batteries will continue to grow steadily with CAGR of 12% reaching ca. 2700 Mm² in 2025 [5]. A major contribution to this growth will come from the needs of electric vehicles and buses (see Figure 11).

From >900 Mm² in 2015 to 2700 Mm² in 2025
 CAGR: +12%

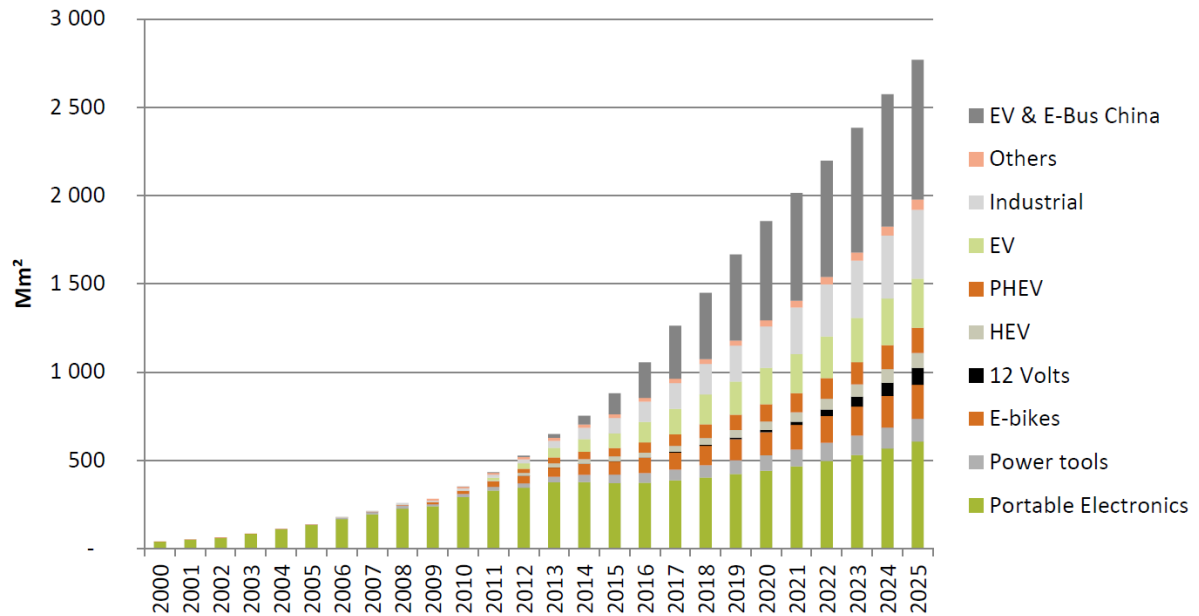


Figure 11: Projected separator market growth (Used with permission from Avicenne Energy [5]).

3.2.5 Future cell chemistries

Significant research effort is dedicated world-wide to the development of several future cell chemistries which have the potential to outperform contemporary Li-ion cells. Chemistries which are often identified as the ones capable of advancing battery technology to beyond the Li-ion include:

- a) Lithium metal (Li metal) batteries
- b) Solid State batteries (SSB)
- c) Lithium-sulphur (Li-S) batteries
- d) Lithium-air (Li-air) batteries

The development status as well as challenges facing these chemistries are briefly outlined in the following sections.

Li metal [30]

With a specific capacity more than ten times that of the LiC_6 anode used in present-day lithium-ion batteries, cells based on Li metal anodes are of particular interest. Effective strategies for stabilizing the anode in such cells are required for progress on future storage technologies, including Li-S and Li-air batteries. Several challenges — parasitic reactions of Li metal with liquid electrolytes, unstable and dendritic electrodeposition, and dendrite-induced short circuits — derailed early efforts to commercialize lithium metal batteries.

Recent research efforts to minimise reactions between the metal and electrolyte use surface coatings to alter the composition and ion transport properties of the solid electrolyte interface (SEI) layer and are expected to yield lithium-metal batteries based on layered hybrid electrolytes in which Li anodes, protected by an artificial SEI, coexist with conventional liquid electrolytes. Artificial SEI designs which can also be applicable to other reactive metal anodes, e.g. Na, Al or Zn, are of particular interest because these anodes exhibit similar parasitic reactions to Li.

In the longer term, the inherent design flexibility that comes from the malleability of Li will be exploited allowing Li metal batteries to be lithographed, 3D printed, gelled from sols, or integrated into load-bearing structures through layer-by-layer deposition or self-assembly. Design of Li-metal anodes compatible with manufacturing outside the glove box will emerge as an area of high priority.

Solid State batteries [31]

Solid-state batteries (SSBs) that use solid electrolytes (SEs) (either inorganic or polymer) instead of liquid ones could offer both high energy and high power density. SEs allow transfer of lithium ions only and act as functional separators with only minor self-discharge (due to negligible electronic conductivity). Moreover, lithium ions and anions are mobile in liquid electrolytes, causing severe concentration gradients of the conducting salts during current flow and limiting the cell current, whereas only lithium ions are mobile in SEs so this bulk polarization cannot occur. As a result higher current densities and quicker charging times are conceivable in SSBs. Some inorganic solid electrolytes are stable at elevated temperatures, improving battery safety. The mechanical rigidity of SEs may prevent the dendrite formation that is caused by the electrodeposition of lithium, and thus facilitate the use of lithium-metal anodes.

Despite fast growing interest in SSBs, many challenges remain in both manufacturing and fundamental understanding of the technology. For example, lithium-ion conductivity of the polymer electrolytes is too low for battery operation at room temperature, and the

operation in electric vehicles requires temperatures above 80 °C. Even then, their rate capability is limited, preventing fast charging. Hence, the search for stable polymer electrolytes for use with lithium-metal anodes and lithium nickel cobalt manganese oxide or lithium nickel cobalt aluminum oxide cathodes at ambient temperature at sufficient C-rates is one of the challenges scientists and engineers face in the forthcoming years.

The major drawback of many inorganic SEs is their low thermodynamic stability. Most solid electrolytes are easily reduced at low potentials (for example, by lithium metal) — just like their liquid competitors — and oxidized at intermediate potentials. Protecting interphases are therefore required to stabilize the electrolyte/electrode contact, as happens in conventional lithium-ion batteries.

Li-S [32]

Li-S batteries based on abundant sulphur, high-capacity sulphur-containing cathodes and lithium anodes are considered among the most promising candidates to achieve a low-cost and high-energy-density system. Fundamental challenges facing Li-S batteries originate from the insulating properties of elemental sulphur and lithium sulphides, the dissolution of lithium polysulphides in the electrolyte, the volume change at the cathode on cycling and the need to passivate membranes at the anode to inhibit dendrite formation. Moreover, it is now widely realized that high sulphur loading electrodes are essential for Li-S technology in the marketplace.

Li-air [33]

The Li-air battery, which uses oxygen from air, has the highest theoretical specific energy density of any battery technology, 3,500 Wh/kg. Estimates of practical energy storage are uncertain, as many factors are unknown, but values in the range 500 to 1,000 Wh/kg – sufficient to deliver significantly in excess of a 500 km driving range if deployed in an electric vehicle battery – have been proposed. Despite significant research over the past decade, there is a lack of a true understanding of the underpinning chemistry and electrochemical processes in Li-air batteries. Li-air batteries combine two challenging electrodes, Li metal and oxygen. Li-metal electrodes still do not deliver the necessary cycling efficiency (ratio of discharge/charge capacity) and related suppression of dendrites. Aprotic Li-O₂ faces a number of challenges, not least of which is the stability of the electrolyte solution and the cathode towards reduced oxygen species. Also, the issue of air handling and filtering would need to be addressed by new engineering solutions.

Technology evolution [34]

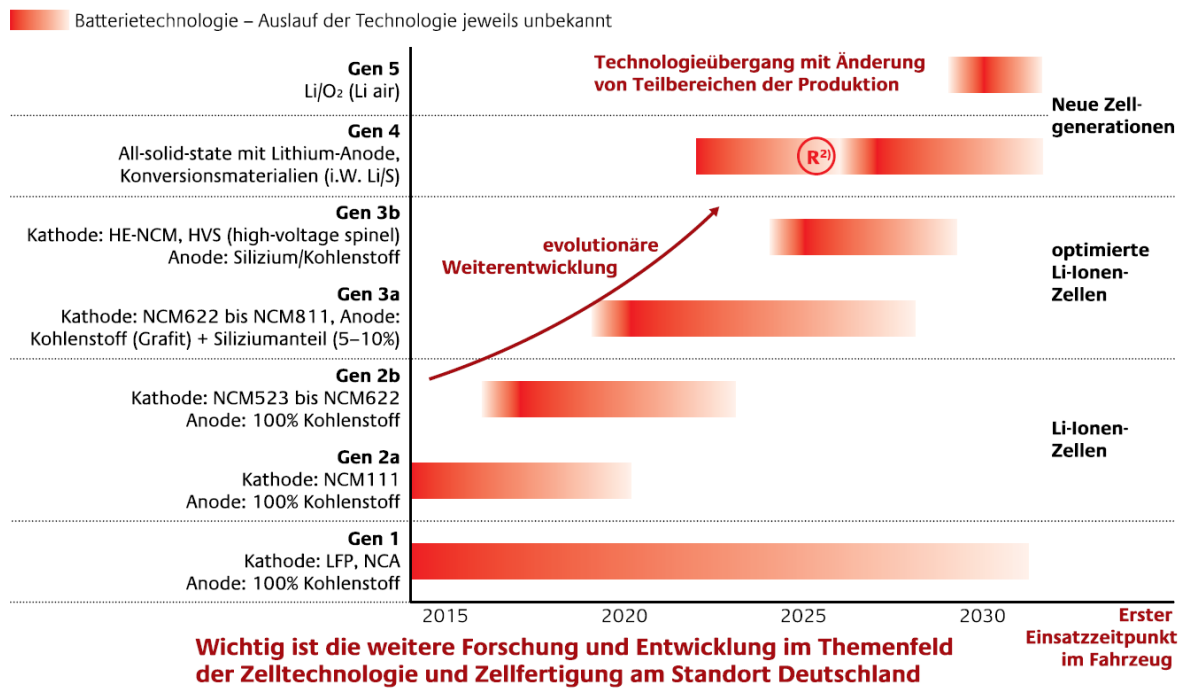
Given the numerous fundamental challenges facing the above-listed future battery chemistries, and taking into account that time-to-market for new battery materials and concepts has historically been shown to range between 10 and 20 years [5], projections regarding the commercialisation timeline of the future technologies need to be made with caution. According to the German National Platform for Electromobility contemporary Li-ion cells (generations 1 and 2a in Figure 12), largely based on LFP, LMO, NCA and NMC cathodes and graphite or carbon anodes, will soon be gradually substituted by generation 2b technology with nickel-rich cathodes and higher energy density.

Another advance is to be expected with the introduction of Generation 3, which is characterized by the use of carbon-silicon anodes. Generations 3a and 3b can be expected to subsequently upper the cut-off voltage, which will lead to an increase in energy density.

In the medium to long term, a doubling of range or halving of costs appears to be possible especially with traction battery cells of Generation 4. If the challenges related to solid state and lithium-sulphur technology (and other conversion chemistries (Generation 4)) are resolved, they can become important parallel technologies co-existing with lithium-ion on the market (see Figure 12).

It is still largely an open question whether the theoretically proven advantage of the higher energy density at the cellular level can be efficiently implemented at a battery pack level. Therefore, at present a question whether and when a transition to "post" lithium-ion technology (traction battery cells with conversion materials (Generation 4) and lithium-air (Generation 5)) will take place in future cannot be answered with certainty. From today's perspective advancement to solid state systems in the near future (Generation 4) looks more likely.

For all of these chemistries no significant manufacturing base has yet been developed by any global economy. This leaves a potential opportunity open for Europe to break-in to cell manufacturing for chemistries where currently no significant barrier to entry exists.



NCM: Lithium-Nickel-Cobalt-Manganoxid, NCA: Lithium-Nickel-Cobalt-Aluminiumoxid, LFP: Lithium-Eisenphosphat
 1) Offene Systeme wie Li/O₂-Batterien werden für automotiv Anwendungen sehr kritisch gesehen. Daher ist eine Verwendung dieser Speichersysteme für automotiv Anwendungen sehr unwahrscheinlich 2) Risiko einer früheren Marktverfügbarkeit
 Quelle: (acatech – Deutsche Akademie der Technikwissenschaften, 2015), NPE UAG 2.2 M. Weiss, Mitglieder (2015)

Figure 12: Forecasted battery technology evolution [34]

3.3 Cell manufacturing

3.3.1 Cell manufacturing – current status

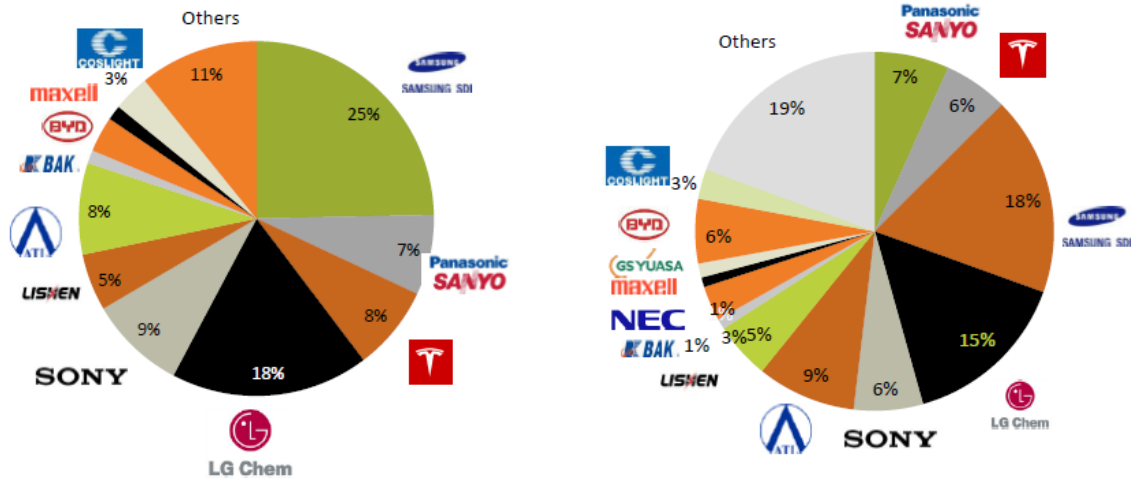
The total sales volume of Li-ion battery cells in 2015 was ca. 5,600 million cells (equivalent to ca. 60 GWh) and the cell market value was ca. B\$ 16.7, its compound annual growth rate (CAGR) amounted to 22% for volume and 15% in value between 2005 and 2015 [5]. In 2015 approximately 31% of the total Li-ion battery cell sales, equivalent to more than 18 GWh in volume and ca. B\$ 5.3 in value, were used in automotive applications [5]. This number excludes Li-ion battery cells for SLI (Starting, Lighting and Ignition) application, which at present has a very minor market share, but is expected to grow in the future [5].

Lithium-ion batteries were first commercialised in the early 1990s by Sony. Their uptake grew rapidly as they delivered a superior performance relative to other rechargeable chemistries deployed at the time. The surge in demand, in terms of number and product range, for portable electronic devices drove the corresponding need for high performance lithium ion batteries. Asian battery manufacturers' dominance in this market positioned them favourably to respond quickly and competitively to the growing demand. This allowed establishment of a strong manufacturing base in Asia, which later enabled quick scaling up of the production volume, further development and optimisation of the technology and diversification of their product range toward emerging markets, including automotive [35]. Asian companies, notably Samsung SDI (KR), LG Chem (KR), Sanyo-Panasonic (JP), Sony (JP) and BYD (CN) among others, dominate the Li-ion battery cell manufacturing (see Figure 13) [5, 34, 35].

Cell manufacturers for automotive applications include Panasonic (JP), Samsung SDI (KR), LG Chem (KR), AESC (JP), GS Yuasa (JP), Li Energy Japan (JP), BYD (CN), Wanxiang (CN), Lishen Tianjin (CN) and Toshiba (JP) [26, 34, 36].

The worldwide Li-ion battery market Company market share in 2015 in volume: 5600 M cells

The worldwide Li-ion battery market Company market share in 2015 in value⁽¹⁾ – 16,7 B\$



Company	Market volume in 2015, million cells	Company	Market value in 2015, million US \$
Samsung SDI	1376	Samsung SDI	3000
LG Chem	1008	LG Chem	2530
SONY	490	ATL	1490
ATL	465	Sanyo-	1125
Tesla	430	BYD	1120
Sanyo-	408	SONY	1040
Lishen	290	Tesla	970
Coslight	185	Lishen	850
BYD	180	NEC	520
Maxell	76	Coslight	450
BAK	67	GS Yuasa	210
Other	625	Other	3395
Total	5600	Total	16700

Figure 13: Market share of various Li-ion cell producers in 2015, left – in volume, right – in value. (Used with permission from Avicenne Energy [5])

Table 2 illustrates the total completed, under construction and planned Li-ion cell manufacturing capacities in various regions in 2014 according to the data cited in reports of the US Clean Energy Manufacturing Analysis Center (CEMAC) [7, 37]. As can be seen, in 2014 the global manufacturing capacity for Li-ion battery cells for all applications was ca. 76.3 GWh and 88% of this manufacturing capacity was located in Japan, China and South Korea (see Table 2). Production capacity for automotive Li-ion cells was 27.5 GWh in 2014, 79% of which was located in Asia [7, 37]. A similar number for the global production capacity for automotive Li-ion battery cells - 27.2 GWh- is quoted by the German National Platform for Electromobility [34].

According to Avicenne Energy, the global production capacity for Li-ion battery cells for all applications was approximately 100 GWh in 2015, from which 40 GWh were for portable Li-ion cells and 60 GWh for all other applications including automotive [5].

In the time period from 2014 to 2016 the global manufacturing capacity for automotive Li-ion cells has increased significantly (compare Table 2 and Table 3) [6, 38]. Korea has increased its manufacturing capacity for automotive cells ca. 1.5 times, Japan ca. 2.4 times and China 2.7 times from 2014 to 2016. China plans further expansion of its manufacturing capacity for lithium-ion battery cells and has announced construction of extra 19.3 GWh manufacturing capacity in addition to its 30.4 GWh. Especially aggressive growth in the manufacturing capacity for automotive cells is observed in the USA, where an explosive growth of the manufacturing capacity increasing almost 10 times from 2014 to 2016 is observed thanks to construction of the Tesla Gigafactory. The fully commissioned manufacturing capacity of the EU has not changed significantly. Please note that 5 GWh capacity mentioned as "under construction" in the CEMAC reports [7, 37] refers to a new BMZ Li-ion battery manufacturing facility in Karlstein (DE) (see section 3.4).

Table 2: Annual manufacturing capacity of Li-ion cells worldwide in 2014 [7, 37]

	Fully commissioned (GWh)	Partially commissioned (GWh)	Under construction (GWh)	Announced (GWh)	Total manufacturing capacity* (GWh)	Share of total global capacity*	Automotive manufacturing capacity* (GWh)	Share of global automotive capacity*
China	16.704	3.576	18.730	12.847	39.010	51 %	11.240	41 %
Japan	10.778	0	1.200	0	11.978	16 %	5.750	21 %
Korea	16.059	0	0	0	16.059	21 %	4.600	17 %
U.S.	3.770	0	1.200	35.0	4.970	7 %	4.600	17 %
EU**	1.798	0	0	0	1.798	2 %	1.300	5 %
Rest of world	2.440	0	0	0.564	2.440	3 %	0	0 %
TOTAL	51.549	3.576	21.130	48.412	76.255	100 %	27.490	100 %

* includes fully commissioned, partially commissioned and under construction capacity; excludes announced capacity

**Please note that JRC analysis of the underlying data for the EU indicated that numbers for the EU include data on pack manufacturing [38].

Table 3: Annual manufacturing capacity of automotive Li-ion cells worldwide in 2016 [6, 38]

	Fully commissioned (GWh)	Partially commissioned (GWh)	Under construction (GWh)	Announced (GWh)	Total manufacturing capacity* (GWh)	Increase compared to 2014 (%)
China	11.152	3.038	16.244	19.246	30.434	271
Japan	13.623				13.623	237
Korea	6.570				6.570	143
U.S.	8.925	8.750	26.250	0.150	43.925	955
EU**	1.293		5.000		6.293	0
Rest of world	3.390			0.120	3.390	139
TOTAL	44.953	11.788	47.494	19.516	104.235	

* includes fully commissioned, partially commissioned and under construction capacity; excludes announced capacity

**Please note that JRC analysis of the underlying data for the EU indicated that numbers for the EU include data on pack manufacturing; 5 GWh capacity mentioned as "under construction" refers to a new BMZ Li-ion battery manufacturing facility in Karlstein (DE) (see section 3.4) [38].

The EU does not have a significant manufacturing capacity for Li-ion battery cells and published data on capacity and on actual production differ slightly depending on the sources:

a) According to the US Clean Energy Manufacturing Analysis Center (CEMAC) whose reports are based on data from Bloomberg New Energy Finance (BNEF), the total production capacity of fully commissioned facilities in Europe was nearly 1.8 GWh/year in 2014 (corresponding to 2% in the global production capacity of Li-ion cells for all applications) out of which 1.3 GWh/year were for automotive Li-ion cells (corresponding to 5 % of the global production capacity of automotive Li-ion cells) (see Table 2) [7, 37]. (Please note that JRC analysis of the underlying data for the EU indicated that numbers for the EU include data on pack manufacturing [38]).

b) In its "Roadmap integrated cell and battery production Germany" the German National Platform for Electromobility indicates that EU's production capacity for large format Li-ion cells for automotive and energy storage applications was 1.5 GWh/year in 2014 [34]. This number, based on Roland Berger's data, takes into account only an estimate of production capacity of AESC (Nissan) facility in Sunderland (UK) [34].

c) According to the analysis of Avicenne Energy, manufacturing capacity for Li-ion cells in Europe was nearly 1.5 GWh/year in 2015 [5], distributed over a number of relatively small producers, however it quotes the actual production volume of Li-ion cells in Europe at only ca. 350 MWh [5].

Compared with Asian counterparts the number and relative size of European Li-ion cell manufacturing companies are significantly smaller. These manufacturers include (see also Table 4):

- SAFT, recently taken over by Total [39], is currently the largest active European producer of Li-ion cells. Its manufacturing facility in Nersac (FR) has a production capacity of 60 MWh/year [5, 40], however SAFT's actual production volume in 2015 was 84 MWh, exceeding its nominal capacity [5]. SAFT cells and batteries are used for various applications including space, military and aircraft applications [41].
- ABSL Power Solutions in Culham (UK), recently acquired by EnerSys, is a European manufacturer of Li-ion battery cells for space applications [42].
- AGM Batteries Ltd. in Thurso (UK) develops and manufactures rechargeable Li-ion cells and non-rechargeable lithium cells. Its production facility with capacity of 50 MWh supplies Li-ion batteries across a range of markets including defence, oil and gas markets [43].

- Switzerland-based Leclanché operates a production facility in Willstätt (DE), where it produces Li-ion cells and batteries for energy storage applications. The current manufacturing capacity of this facility is 100 MWh [44].
- EAS Germany GmbH, located in Nordhausen, Germany, produces cylindrical cells, which are currently deployed in space, submarine, marine and automotive applications in Europe, Asia and North America [45]. Production capacity of this facility is 100 MWh/year while actual the production in 2015 was 40 MWh [46].
- Litarion GmbH, a subsidiary of Electrovaya, in Kamenz (DE), is a supplier of lithium-ion cells for mobile and stationary energy storage and other demanding applications. Furthermore, Litarion has manufacturing capacity to produce electrodes and ceramic separators as key components for high performance lithium-ion battery cells [29]. Production capacity of this facility for cells is 500 MWh/year, actual production in 2015 was ca. 25 MWh [46].
- Custom Cells Itzehoe GmbH, located in Itzehoe (DE), produces Li-ion pouch cells for various applications and of various formats, specified by the customers [47]. Production capacity of this facility is 20 MWh/year, actual production in 2015 – 1 MWh [46].
- SSL Energie GmbH in Kelheim (DE) manufactures Li-ion cells for energy storage solutions for telecommunication and industrial plants, as well as for electromobility applications (on land and on water) [48]. Production capacity of this facility is 0.1 MWh/year while the actual production in 2015 was negligible [46].
- Liacon GmbH, located in Itzehoe (DE), has a vertically integrated production plant for large-scale lithium titanate polymer cells [49].
- VARTA Microbattery GmbH, located in Ellwangen (DE), is a manufacturer of microbatteries and is one of the market leaders in the hearing aid battery and nickel-metal hydride and lithium-ion coin battery segments [50].
- European Battery Technologies Oy in Varkaus (FI) develops and manufactures large, rechargeable lithium-ion based prismatic cells and battery systems which can be used to power hybrid and electric drive trains and to store energy produced by renewable energy sources [51]. Production capacity of this facility was 30 MWh/year and the actual production volume amounted to 1 MWh in 2015 [46].
- Advanced Lithium System Europe S.A. (ALSE S.A.) has a manufacturing facility in Xanthi (GR), where Li-ion cells and batteries for defence applications such as exercise torpedoes, are produced [52]. Production capacity of this facility is 100 MWh/year and the actual production volume amounted to 0.1 MWh in 2015 [46].

- A special type of Li-ion cells - solid-state cells with a Li-metal anode – is produced in France and in Canada by Bolloré (FR). The cell production capacity in France is 500 MWh per year and the actual production in 2015 amounted to 120 MWh [46].

Table 4. Li-ion cell actual production volume for 2015 and production capacity of selected European manufacturers. Source: [5, 40] [43] [44] [46].

Company	Actual production in 2015, MWh	Production capacity, MWh
SAFT (FR)	84	60
EAS Germany GmbH (DE)	40	100
Litarion GmbH (DE)	25	500
Leclanché GmbH (DE)	5	100
European Battery Technologies Oy (FI)	1	30
Custom Cells Itzehoe GmbH (DE)	1	20
Advanced Lithium System Europe S.A. (GR)	0.1	100
AGM Batteries Ltd. (UK)	n.a.	50
SSL Energie GmbH (DE)	negligible	0.1
Bolloré (FR)	120	500
Total	276.1	1460.1

Due to the high production costs Daimler subsidiary Li-Tec (DE) stopped production of Li-ion battery cells and batteries at the end of 2015, marking the closure of the only German factory producing cells for EVs [36, 53]. According to data of BNEF the manufacturing capacity of this factory was 480 MWh [38].

Renault, CEA (French Atomic Energy and Alternative Energies Commission), and Nissan were planning to build a factory in Flins (France) to produce automotive Li-ion cells and batteries, with an annual manufacturing capacity of 100,000 batteries [54]. This cell and

battery production plant foreseen to supply batteries for Renault's ZOE electric vehicle, was delayed due to technical constraints [55]. At present only a battery pack assembly line is operational at this location [56]. In 2009 Renault Nissan announced it would build an advanced Li-ion electric vehicle battery factory in Cacia (Aveiro, Portugal) to produce 50,000 batteries per year starting in 2012 [57]. However, this plan did not go ahead and the facility is currently still not operational [58].

In the meantime, mature Asian cell manufacturers are planning to establish Li-ion automotive cell and battery production in the EU. For example, LG Chem (KR) plans to build a production plant in Poland (most likely in Wrocław) with an annual production capacity of 50,000 Li-ion automotive batteries [59, 60]. Samsung SDI (KR) has started preparing for Li-ion battery (cell, module and pack) production in Jaszfenyszaru, Hungary [61].

3.3.2 Projected market growth

The Li-ion battery cell market is forecasted to grow rapidly in the coming years reaching ca. 140 GWh in volume and ca. B\$ 28.5 in value by 2020 and ca. 215 GWh and B\$ 35.5 by 2025, respectively, according to the data of Avicenne Energy [5]. The automotive part of the market is predicted to grow to nearly 76 GWh in volume and B\$ 15 in value by 2020 and 121 GWh and B\$ 20 by 2025, respectively [5]. Major contribution to the anticipated growth of the Li-ion cell market for electric vehicle is expected to come from China. Indeed, it is forecasted that ca. 2/3 of the automotive Li-ion cells produced (or approximately 80 GWh) will be used to power electric vehicles in China in 2025 [5]. Considering only the necessity to reduce transport CO₂ emissions defined by the regulations the German National Platform for Electromobility forecasts that the global market of Li-ion automotive cells will grow even quicker and reach 150 GWh in 2025 ("conservative scenario"^{††}) [34]. When other factors, such as governmental financial incentives, are taken into account growth of the market to 400 GWh by 2025 is expected ("optimistic scenario"^{††}) [34]. Demand for automotive Li-ion cells by European OEMs for BEVs and PHEVs production is estimated to be ca. 15-28 GWh in 2021 and ca. 37-117 GWh in 2025 for the two scenarios considered [34].

^{††} The conservative scenario is based on the required minimum sales of electric vehicles to meet the regional limits on CO₂ emissions. No governmental subsidies of the purchase and maintenance costs of BEVs and PHEVs are considered.

^{††} In the optimistic scenario governmental incentives for promotion of PHEVs and BEVs are considered in addition to the regional requirements on CO₂ emissions. This results in a cost advantage of PHEVs and BEVs over conventional powertrains.

3.3.3 Global cell production over-capacity

Comparing data on the manufacturing capacity for automotive Li-ion cells in 2014, ca. 27,5 GWh [7, 34, 37], to the corresponding demand and sales volume, 10-11 GWh [27, 28, 34], it can be seen that a noticeable global production overcapacity existed in 2014.

Production overcapacity is, however, not unique for Li-ion cell for automotive applications. In fact, a global manufacturing overcapacity, albeit to a lower degree, is seen for all types of Li-ion cells and even in the mature and well-established lead-acid battery sector (see Figure 14) [5].

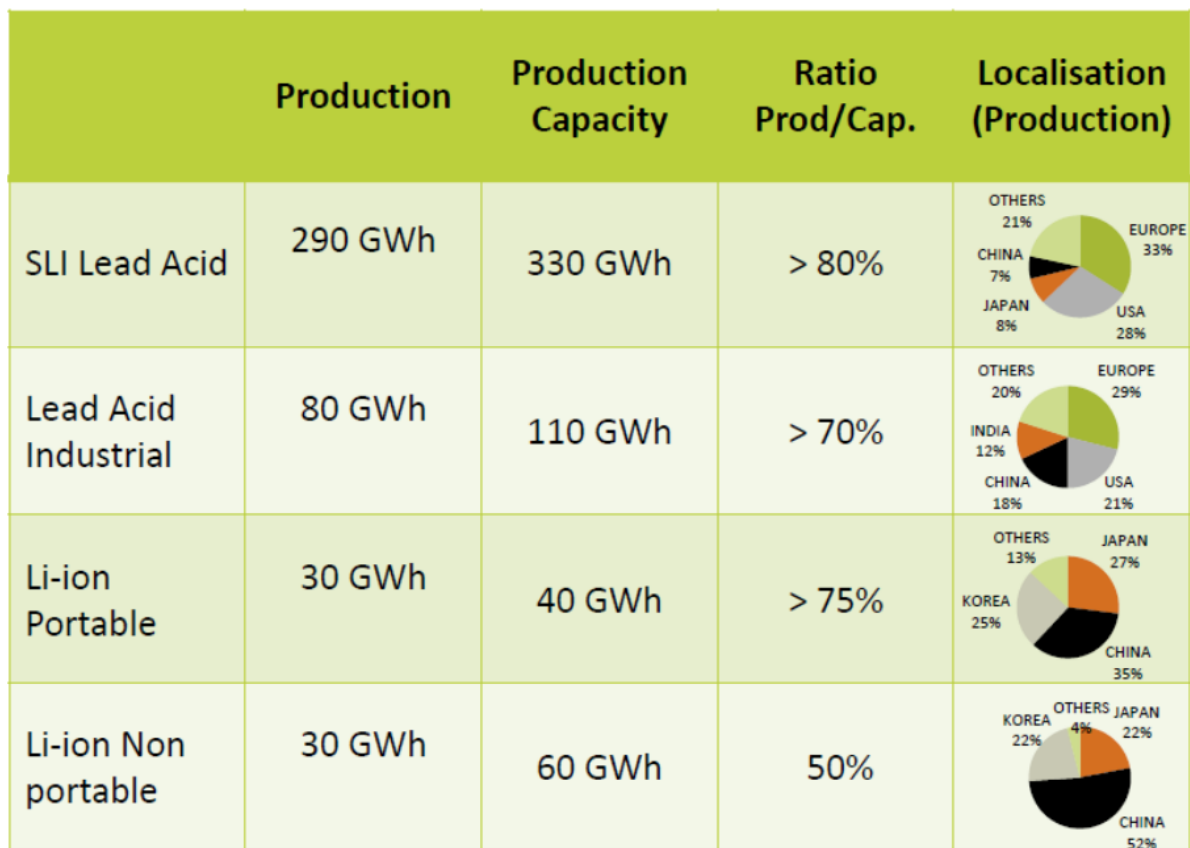


Figure 14: Battery cell production capacity (Used with permission from Avicenne Energy [5]).

Global overcapacity for automotive Li-ion cells was unevenly divided among the regions in 2014 as shown in Figure 15 [7, 37]. The lowest utilisation of the manufacturing facilities for automotive Li-ion cells – ca. 10% - was observed for China and the highest utilisation – ca. 40% and 30% - for Japan and Korea, respectively. Utilisation for US and EU was around 20% [7, 37]. Analysis by Avicenne Energy shows that domestic European Li-ion cell manufacturing facilities continued to be under-utilised also in 2015 [46].

A possible reason for the current cell manufacturing over-capacity [6] may be that high profitability of a supply chain segment covering a promising growing product/service will

naturally encourage investments in capacity expansion. Also, as explained in [7, 37]: "Initially overly optimistic assumptions regarding electric vehicle demand have contributed to an overbuild of large format Li-ion battery cell production capacity targeted at vehicle markets".

The observed global production overcapacity for automotive Li-ion battery cells has likely led European battery manufacturers and automotive OEMs to conclude in 2013 that "Current estimates suggest that international resources would be sufficient for the EU to fulfil demand for hybrid electric and full electric vehicles for the foreseeable future" [62].

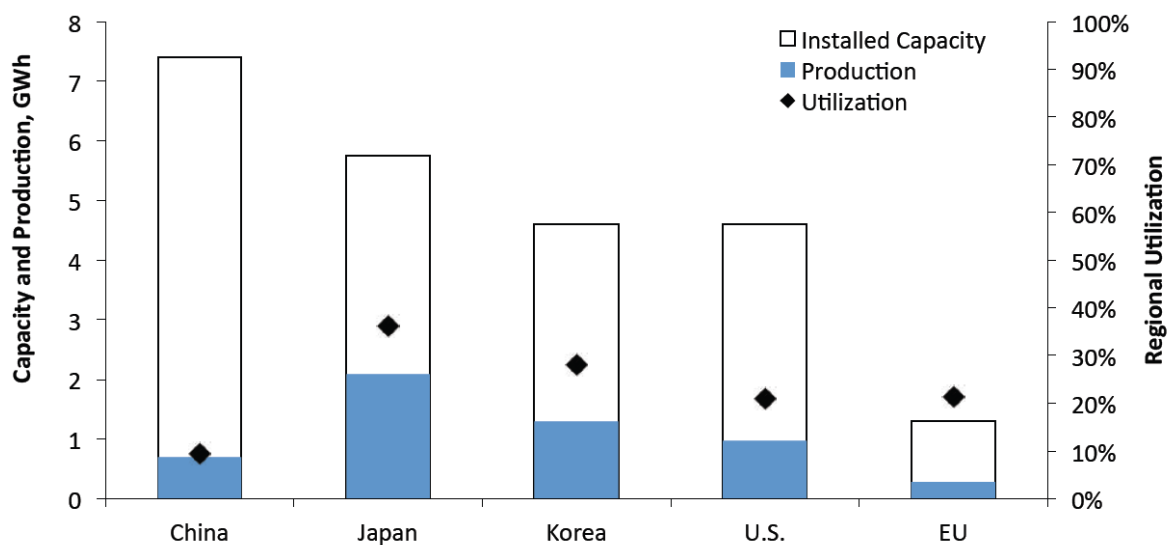


Figure 15: Automotive Li-ion battery cell manufacturing capacity and utilization in 2014. Source:[7, 37].

This position was recently reiterated by Daimler's CEO according to Automotive News website post from February 2016 [63]: "Daimler CEO Dieter Zetsche ruled out investing in battery cell production for electric cars with other German premium brands for at least another few years, citing a massive overcapacity in the market that has turned cells into a commodity. "The dumbest thing we could do is to add to that overcapacity," Zetsche said earlier this month in Stuttgart. "Contrary to the expectation four or six years ago when everyone thought that the cells would be a rarity that could even be used as a tool of industrial policy, there is de facto a massive overcapacity in the market today and cells have become a commodity," he said".

Nevertheless, another automotive OEM – Volkswagen Group and also its brand Audi – has recently expressed interest in domestic production of Li-ion cells for electric vehicles [63-66].

According to CEMAC the market situation is expected to come into better balance in the near future, with global overcapacity decreasing in 2016 [6]. Taking into account projected market growth for automotive Li-ion cells and assuming the production capacity remains at the present level, CEMAC has estimated that the need for new capacity will arise in 2019-2020 (see Figure 16) [6].

However, data presented in the same report by CEMAC [6] also suggests that manufacturing capacity is likely to continue growing, and overcapacity conditions may persist. Nearly 25 GWh of capacity is currently either partially commissioned or under construction, and a further 55 GWh of capacity has been announced.

Also the German National Platform for Electromobility has come to the conclusion that, even considering today's excess of manufacturing capacity for automotive Li-ion battery cells, a significant need for additional cell production capacity may be expected to arise from about 2020 (see Figure 17) [34]. According to the data published in [34], there will be worldwide^{§§} additional demand of about 5 GWh/year in 2020 and up to 100 GWh/year by 2025 in the conservative scenario. In the optimistic scenario the demand increases to above 300 GWh/year. Further demand is generated by buses and stationary applications. This situation opens up the possibility for competition-enabled cell production also in Europe (Figure 17) [34].

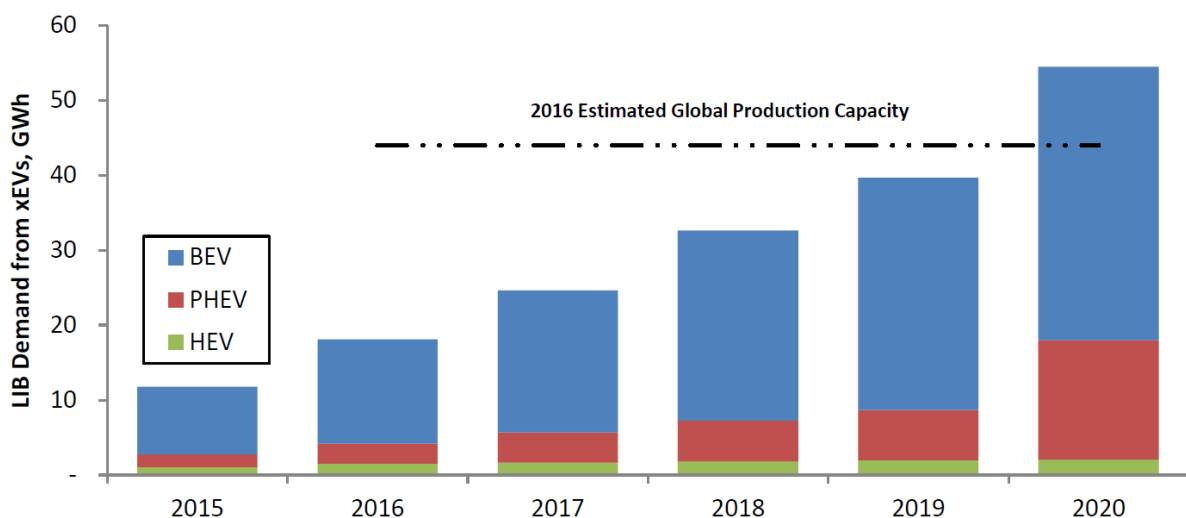


Figure 16: Estimated electric vehicle Li-ion battery cell demand and global automotive Li-ion battery cell manufacturing capacity [6].

^{§§} Following world regions are considered: Europe, Japan and South Korea, China, Canada, USA and Mexico. Their demand covers more than 90% of the total world demand.

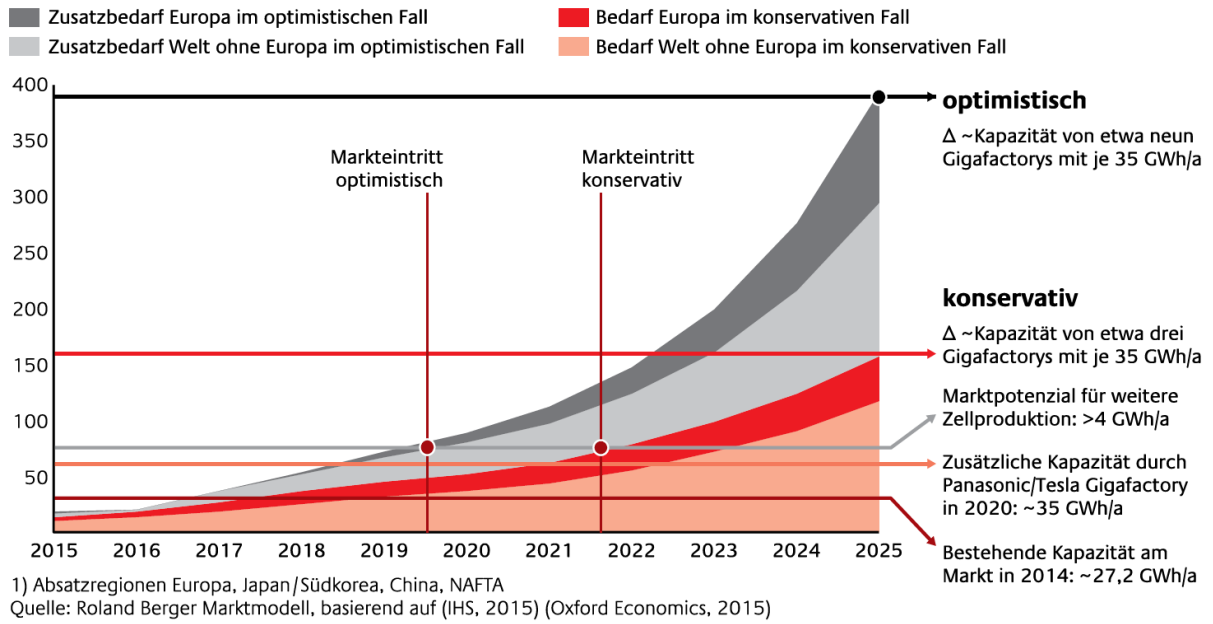


Figure 17: Worldwide demand for automotive Li-ion battery cells in 2015-2025. Source:[34].

3.4 Battery pack manufacturing

The battery pack is a key part of the EV power train, accounting for around 30% of the total vehicle value. The Li-ion battery pack market for all applications was more than B\$ 22 in value in 2015 and the automotive share was slightly less than 8 B\$ [5]. The automotive battery pack market value is expected to grow to ca. B\$ 21.3 in 2020 [5, 8] and ca. B\$ 27.3 in 2025 [5] (see Figure 18).

Battery pack manufacturing accounts for approximately 40 % of the total cost of the battery pack [37]. As a whole, all the components of the electric powertrain (electric engine, power electronics, battery pack and charging devices) will account for almost half of the global automotive market expansion up to 2020, equivalent to €100 billion [67].

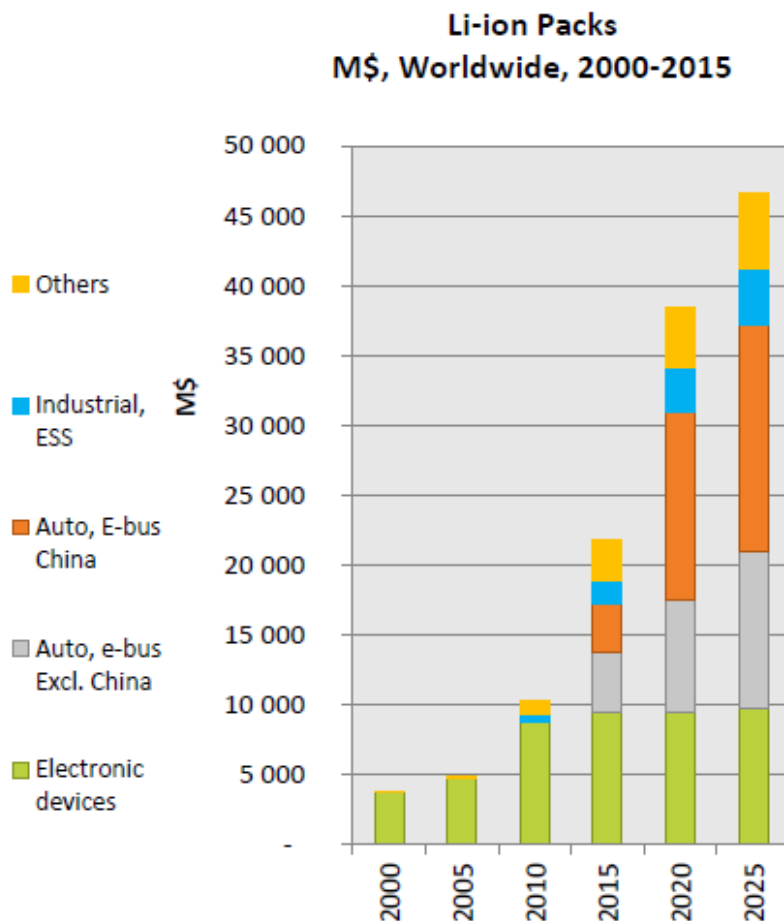


Figure 18: Projected growth of Li-ion pack market (Used with permission from Avicenne Energy [5]).

Different car manufacturers have different strategies whether to invest and develop the required pack manufacturing capacity in-house or to outsource it to specialist suppliers.

The majority of OEMs producing electric vehicle maintain a technological core competence around battery pack design and battery management system to keep some control and profit margins. Consideration of the specific circumstances of the lithium ion cell manufacture value chain in different regions (US, EU, China, Japan) can help explain the different manufacturing strategies adopted by the OEMs located in these regions. Japanese and Chinese OEMs typically keep a higher control on all steps up to the segment of the cell and battery pack manufacturing process whereas European OEMs, who are forced to relinquish control over cell manufacturing due to the absence of significant domestic cell manufacturing capacity, are trying to keep pack design and pack assembly in-house.

Table 5: OEMs Battery pack manufacturing strategy

OEMs battery pack manufacturing strategy and control.				US	CN	EU	JP
Per region:							
Lower control Higher control			
Cells and pack manufacturing completely outsourced.	Cells/modules manufacturing outsourced through Tier 1 suppliers. In-house pack design and manufacturing.	Cells production through joint ventures/controlled subsidiary companies. In-house pack design and manufacturing.	In-house manufacturing of cells, pack design and manufacturing.				
GM	BMW	Nissan	Tesla (plan to)				
	Renault	Mitsubishi	BYD				
	Daimler						

In the US the two main OEMs active in the EV business, Tesla and GM, are adopting opposite strategies as illustrated in Table 5. Tesla (US) is the leader on the BEV-PHEV market despite being less heavily resourced as some of its competitor OEMs. Rather than relying on the Tier 1 and Tier 2 supply chain, Tesla is opting to produce the majority of its key components in its California plant in Fremont. This includes the battery packs for its Tesla S and Tesla X vehicle model using cells supplied by Panasonic (JP). Those models have also the biggest battery pack on the market (with an average energy storage capacity of 90 kWh). For the upcoming Tesla Model 3, the full production of the battery pack (estimated energy storage capacity of 50 kWh) including its cells, is

planned to be performed at the Tesla Gigafactory plant in Nevada. GM, on the other hand, chooses to outsource its entire cell and pack manufacturing including the battery management system.

The Chinese OEM BYD shares a similar strategy as Tesla and is designing, producing and assembling the complete electrical power train system including cells, battery pack and BMS in-house.

In Japan the full battery pack of the Mitsubishi Outlander PHEV is provided by "Lithium Energy Japan", a joint venture between GS Yuasa, Mitsubishi Corporation and Mitsubishi Motors Corporation. The battery pack is thus designed and produced in-house by Mitsubishi albeit through this joint venture. The Nissan Leaf battery pack is supplied by Automotive Energy Supply Corporation (AESC) which is jointly owned by Nissan and the Japanese electronics firm NEC. Similar to Mitsubishi, Nissan designs and manufactures battery packs in-house for its own use. Japanese Li-ion battery pack manufacturing facilities in the EU include Nissan's battery production plant in Sunderland (UK) – the largest of its type in Europe – which became operational in 2013 producing Li-ion batteries for the Nissan Leaf and the Nissan e-NV200 van [68]. The full annual production capacity of this plant is 50,000 EVs and 60,000 battery packs [69].

Within European OEM's, the BMW Group has invested more than €100 million in electric drive technology in Dingolfing (DE) where they set up a plant to manufacture their electric drive systems. BMW designs and develops its core electric drive components including the power electronics, BMS and the whole vehicle electrical system [70] using cells supplied by Samsung SDI. Renault assembles its BEV model, Renault Zoe, in its plant in Flins (FR). The battery pack including the BMS is developed in close partnership with LG Chem who also provides the battery cells [56, 71].

Daimler AG has heavily invested and committed to produce its own line of electric vehicles, challenging BMW and Tesla. Deutsche ACCUMOTIVE, founded in 2009, is a wholly-owned subsidiary of Daimler AG. At its manufacturing facility in Kamenz (DE), the company develops and produces Li-ion traction batteries packs for hybrid and electric vehicles [72]. Since the start of series production in 2012, it has delivered more than 70,000 lithium-ion batteries packs [73]. Daimler AG recently announced it will invest €500 million into the creation of a second lithium-ion battery pack production facility in Kamenz. This new facility will produce lithium-ion batteries packs for use in electric vehicles released under the Mercedes-Benz brand. Daimler currently has a supply agreement arrangement with LG Chem [73] who provides the cells for its battery packs. In addition to supplying batteries for Daimler automobiles, Deutsche ACCUMOTIVE is also entering the stationary battery storage market for residential and industrial applications. The scalability of the systems enables the use of lithium-ion batteries in

large static energy storage systems for network stabilization and smoothing of peak shaving for electricity producers as well as for private households.

LG Chem (KR) supplies the whole battery pack including BMS and thermal management system to General Motors (US) for the Chevrolet Volt. The new Chevrolet Bolt (aimed to compete with the Tesla Model 3) will depend on the same battery pack supply chain and the assembly of the vehicle will most probably be performed outside the US [74].

It is possible to express the volume (expressed in GWh) of automotive battery packs deployed in the sector (quantified on the basis of the energy storage capacity of a battery pack times the number of vehicles sold with this pack) and to make a comparison based on the geographical location where the OEM's headquarters are located (i.e. EU, US, China, Japan and Korea). Such an analysis is illustrated in Figure 19 and Figure 20 using data on the top 20 BEV-PHEV global sales in 2015 [58]. Doing so reveals the very high volume of battery packs deployed in EVs manufactured by US OEMs relative to other regions. The high energy storage capacity of battery packs in the Tesla Model S combined with its high sales ranking explain the US lead in this aspect (Figure 20). The EU has a similar volume compared with Japan and China (Figure 19).

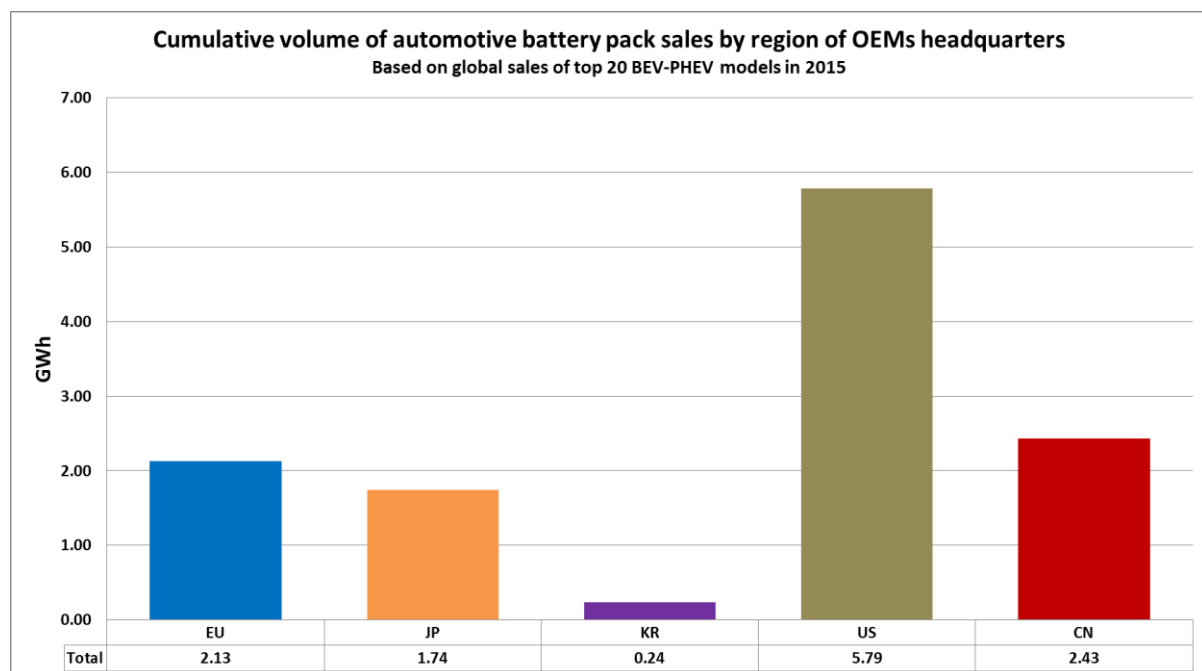


Figure 19: Cumulative volume of automotive battery pack sales by region of OEMs headquarters [75]

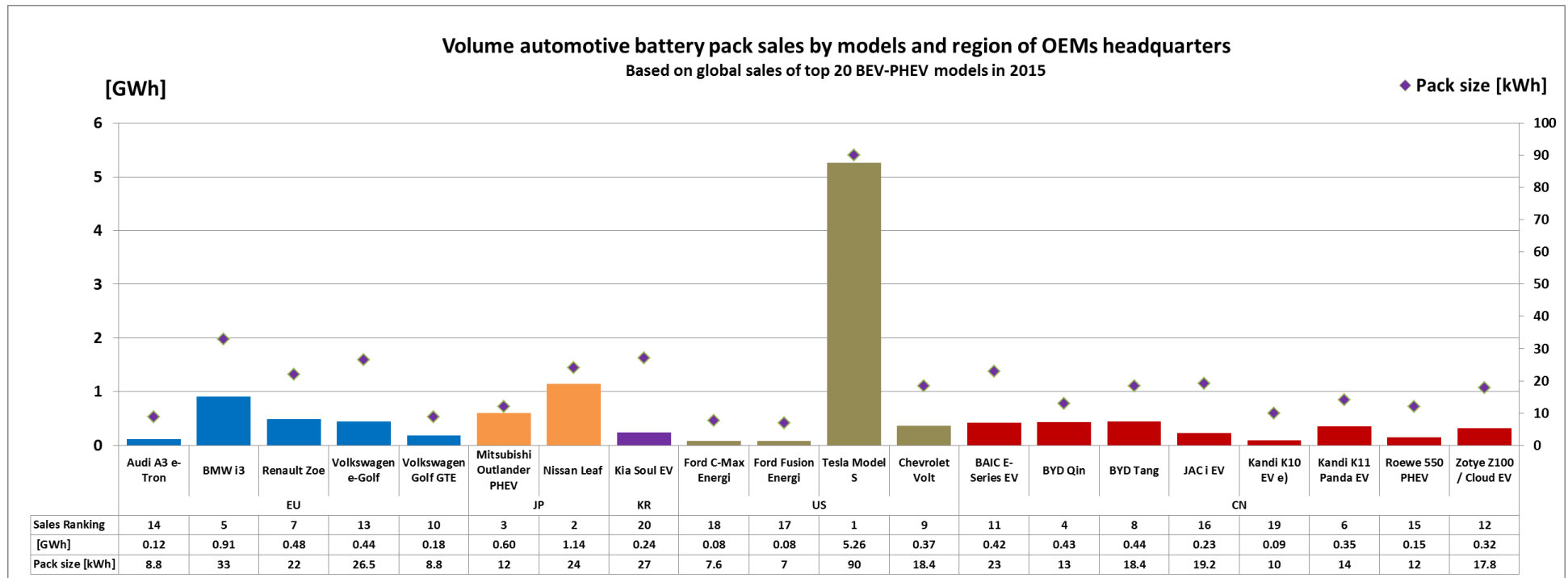


Figure 20: Volume automotive battery pack sales by model and region of OEMs headquarters [75]

Besides the European automotive OEM's with battery pack production interest, other companies with battery pack manufacturing business cases based in Europe worth mentioning include:

- Kreisel Electric GmbH based in Freidstadt, Austria is establishing a business network with German automakers such as BMW and Volkswagen and the British sports carmaker McLaren Automotive. Kreisel Electric manufactures battery packs and electric drive trains for orders up to 10,000 vehicles. They are also designing lithium ion battery production lines for OEMs and creating prototypes for top-tier automakers. Kreisel has started the construction of a new 800MWh battery pack factory for high energy density packs for EVs [76]. Kreisel currently has a supply agreement arrangement with Samsung SDI.
- Johnson Matthey Battery Systems (formerly Axion) (UK) is one of Europe's largest Li-ion battery systems suppliers, processing over 70 million cells a year and supplying volume production of batteries for global markets [70].
- The facility of Continental in Nuremberg (DE) assembles lithium-ion batteries for hybrid electric vehicles such as Mercedes S400 BlueHYBRID [77]. In September 2008, production commenced with a capacity output of 15,000 lithium-ion batteries per annum. Full annual manufacturing capacity of this plant is 333 MWh. The plant incorporates recycling technology that allows at least 50 percent of the content of lithium-ion cells to be recycled [77].
- In 2015 BMZ GmbH has announced expansion of their battery-manufacturing facility in Karlstein (DE) [78] to enable production of up to 80 million lithium-ion batteries of various sizes with a total storage capacity of around 5 GWh annually [78]. This project is expected to be completed by 2020. BMZ GmbH (BMZ) is a battery systems provider whose high-tech batteries are used to power a wide range of products made by leading manufacturers including electric tools, electric vehicles, e-bikes, portable medical devices and batteries for use in the renewable energy sector [78].
- Dow Kokam has completed the construction of a 105 MWh lithium-ion battery manufacturing plant Le Bouchet 2, located in France. This battery facility is designed to manufacture up to 15,000 battery packs of 7 kWh to power 5,000 fully electric vehicles annually (assuming a 21 kWh battery system) [7, 37].
- In 2015 Samsung SDI acquired the EV battery pack business of Magna Steyr, an Austrian-based operating unit of Magna International, including production and development sites [79]. Magna Steyr Battery Systems product portfolio included battery packs for HEVs, PHEVs, BEVs as well as for Heavy Duty Vehicles and 12 V and 48 V systems [80, 81]. In 2014 the manufacturing capacity of Magna Steyr Battery Systems for 16-36 kWh BEV packs was 3,000 units per year, for 6-18

kWh PHEV packs – more than 35,000 units per year and for 0.25-3 kWh HEV packs – 50,000 packs per year [80, 81].

- Bolloré (FR) assembles battery packs for its BlueCar electric vehicles at the facility in Ergue-Gaberic (FR) with manufacturing capacity of 300 MWh [41], [82].

3.5 Electric vehicles manufacturing

3.5.1 Production volumes and deployment

More than 68.5 million passenger vehicles were produced worldwide in 2015 with ca. 24% of these, or more than 16.5 million vehicles, produced in the EU [83].

In recent years the development of hybrid electric vehicle (HEV) batteries has yielded a relatively mature generation of vehicles with ca. 1.9 million HEVs sold worldwide in 2014 and ca. 1.8 million HEVs sold in 2015 [8]. The majority of HEVs are sold in Japan (nearly 60% of the global sales) and USA (ca. 22% of the global sales) resulting in current HEV penetration level of ca. 23% and 3 %, respectively [8, 27, 84]. In Europe ca. 234,000 HEVs were sold in 2015 [8], ca. 1.5% of the total car sales. The leading producer and supplier of HEV, both historically and currently, is Toyota (JP), whose market share in HEV global sales was nearly 70% in 2014 and 2015 [8, 27]. Most of Toyota and Lexus HEV models currently use NiMH traction batteries, but the general market trend is that NiMH traction batteries will gradually be substituted by Li-ion technology [84]. Avicenne Energy forecasts that 50% of HEVs will be equipped with a Li-ion battery by 2020 and 90% of HEVs by 2025 [84].

Production and sales numbers for PHEVs and BEVs increased rapidly in the past few years. Sales numbers cited vary depending on the source. For example, figures cited for worldwide PHEV and BEV sales in 2014 range from ca. 289,000 [85] and to ca. 318,000–390,000 [27, 75], and in 2015 this number increased to ca. 462,000–550,000 [75, 85]. In the EU between ca. 71,000 [86] and 100,000 PHEVs and BEVs [27, 75, 85] were sold in 2014, which corresponds to ca. 22% - 25% of PHEVs and BEVs sold globally. This number doubled in 2015 and reached between 150,000 [86] and 193,500 [75] PHEVs and BEVs sold corresponding to 27% - 35% of PHEVs and BEVs sold globally. On average, the fraction of PHEVs and BEVs in the global passenger vehicle sales in 2015 was ca. 0.8% - 1.1% [85], slightly lower than the ca. 0.9% - 1.3 % average in the EU [87]. It must be noted here, however, that PHEV and BEV penetration levels vary significantly among the world regions [88] and even in the EU among its member states [86, 87], with countries such as Norway, The Netherlands, Denmark, Sweden and USA having a higher fraction of electric vehicles on the road (above 12%, 12%, 8%, 1.7% and 1.9%, respectively) compared to the rest of the world [86, 88].

In 2015 the American Tesla Model S was globally the most sold vehicle among PHEVs and BEVs with a market share of ca. 11%. Tesla was closely followed by two Japanese producers – Nissan with the Nissan Leaf (9% global market share) and Mitsubishi with the Outlander PHEV model (9% market share) [75], ranking 2nd and 3rd, respectively, in the top 20 BEV-PHEV 2015 global sales. Chinese producers were leading in global PHEV and BEV sales in 2015 with 33 % of the market share. BYD is currently the largest electric vehicle manufacturer on China’s automotive market. Automobile business contributed 50% to the company’s revenue in 2015 and nearly half of its 2015 vehicle sales revenue was from EV models [89]. BYD ranks respectively 4th and 8th with its models Qin and Tang in the top 20 BEV-PHEV 2015 global sales. Japanese, USA and EU producers had almost equal market share in PHEV and BEV sales of 21-22% (see Figure 21) [75].

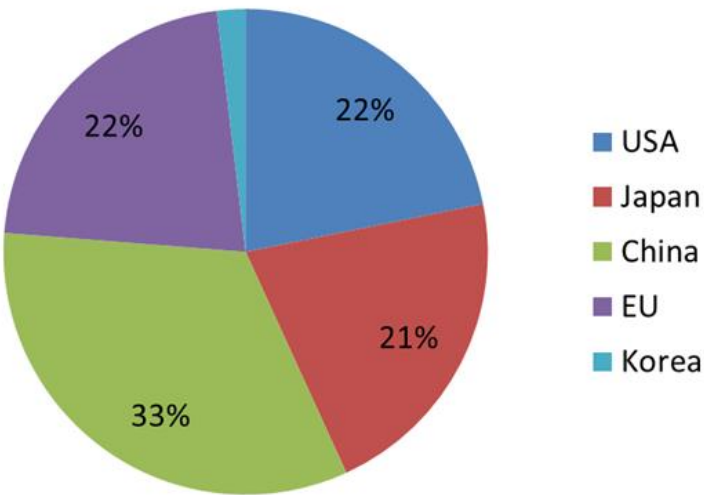


Figure 21: Global market share of the top 20 PHEV and BEV producers, based on [75]. (Producer is assigned to a region according to the location of its Headquarters, e.g. Toyota is considered to be a Japanese producer regardless of whether manufacturing is taking place in Japan or elsewhere)

Among European PHEV and BEV models BMW i3, Renault Zoe and Volkswagen Golf GTE are globally the most sold ranking respectively 5th, 7th and 10th in the top 20 global sales for 2015.

In Europe the Mitsubishi Outlander is the most sold model (ca. 16% share of PHEV and BEV sales), followed by Renault Zoe (10%), Volkswagen Golf GTE (9%), Tesla Model S (9%) and Nissan Leaf (8%) [75].

All categories of electric vehicles – HEVs, PHEVs and BEVs – are expected to gain ground in the future. However, projections on electric vehicles deployment vary among sources and depend strongly on the assumptions made, e.g. what deployment driver is

considered most influential for the number of HEVs, PHEVs and BEVs on the road globally and regionally. For example, UBS's "regulation-driven" forecast as well as the projections of the German National Platform for Electromobility in their "conservative scenario" are based on the necessity to reduce transport CO₂ emissions defined by the regulations [34, 90]. Bloomberg New Energy Finance forecast considers the total cost of ownership for electric vehicles and their economic competitiveness with conventional ICE vehicles as a major factor determining the rate and volume for their deployment [91, 92]. In the following paragraph a non-exhaustive compilation of data available from different sources is presented and discussed.

Figure 22 shows projected global sales of new PHEVs and BEVs for the period between 2015 and 2040. Most of projections do not go beyond 2025, probably due to the high development pace of this market. Figure 23 shows a zoomed view of the time period between 2015 and 2025. It can be seen that projections vary both in absolute numbers and in predicted rate of market growth. For example, Bloomberg and German National Platform for Electromobility (optimistic scenario) predict a steeper growth between 2020 and 2025 than UBS and Avicenne Energy. As for the absolute numbers, the optimistic forecast by the German National Platform for Electromobility falls noticeably higher than other projections while the base case forecast made by Avicenne Energy, which does not take into account strong anticipated growth in China, falls below other projections. Both Avicenne Energy and the German National Platform for Electromobility point out that a rapid growth of Chinese PHEV and BEV market is to be expected in the next decade [27, 28, 34] and therefore projections accounting for this may be more accurate.

In short, conservative projected numbers of global sales for PHEVs and BEVs are ca. 1.5-2.75 M/year in 2020 and ca. 4-6.5 M/year in 2025 (see Figure 23). Europe will have a significant share in this market with sales of new PHEVs and BEVs at 0.7-0.8 M/year in 2020 and 1.65-1.9 M/year in 2025 (see Figure 24), which corresponds to 25-50% of the global sales. Regarding HEV sales, Avicenne Energy forecasts 2.5 M/year to be sold globally in 2020 and 3.2 M/year in 2025 [8] and 0.8 M/year European sales in 2020 and ca. 1.4 M/year in 2025 [84].

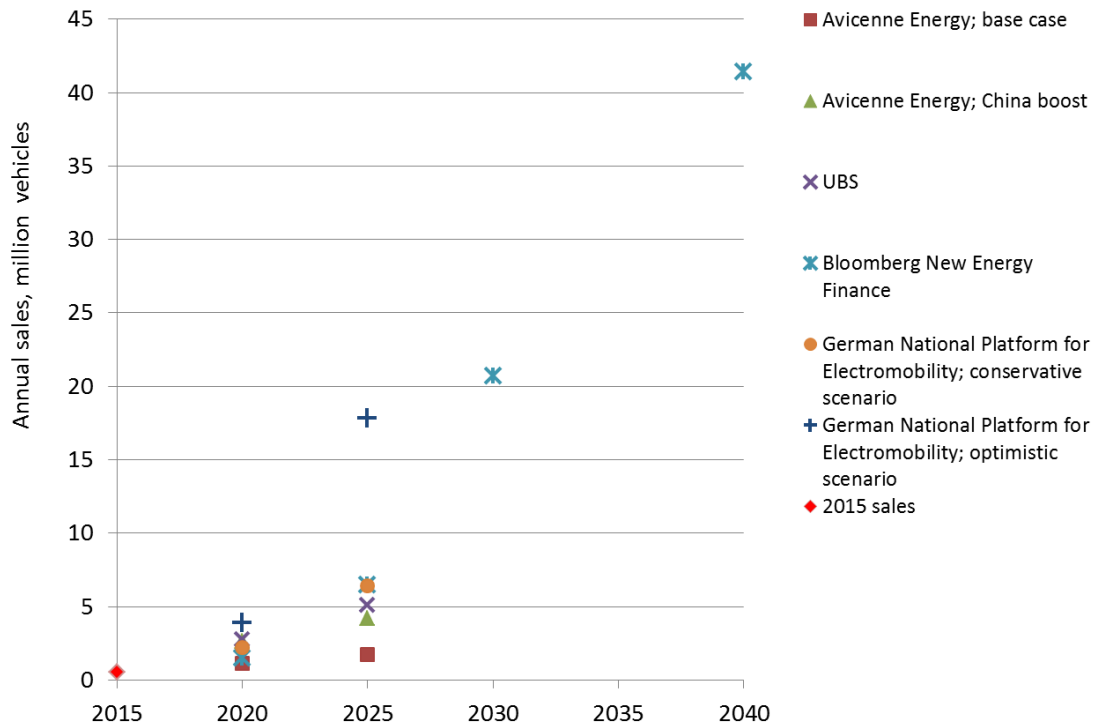


Figure 22: Projected global sales of new PHEV and BEV vehicles. Source [5, 8, 34, 75, 90-92]

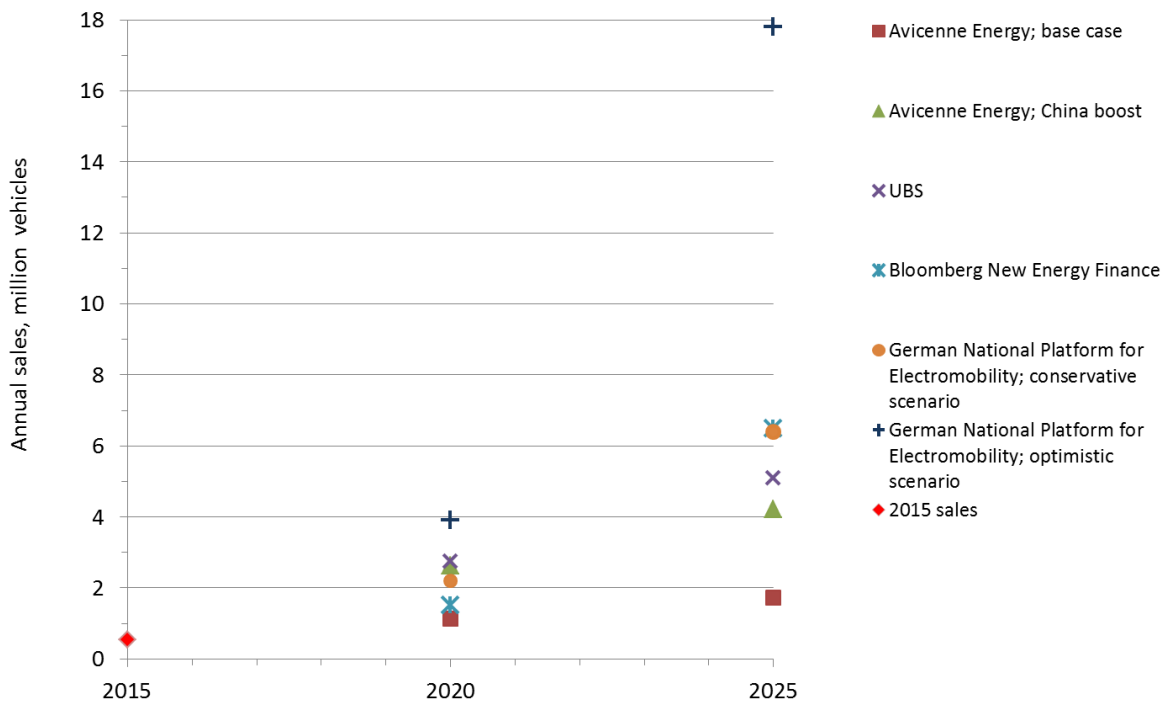


Figure 23: Projected global sales of new PHEV and BEV vehicles for 2015-2025. Source [5, 8, 34, 75, 90-92]

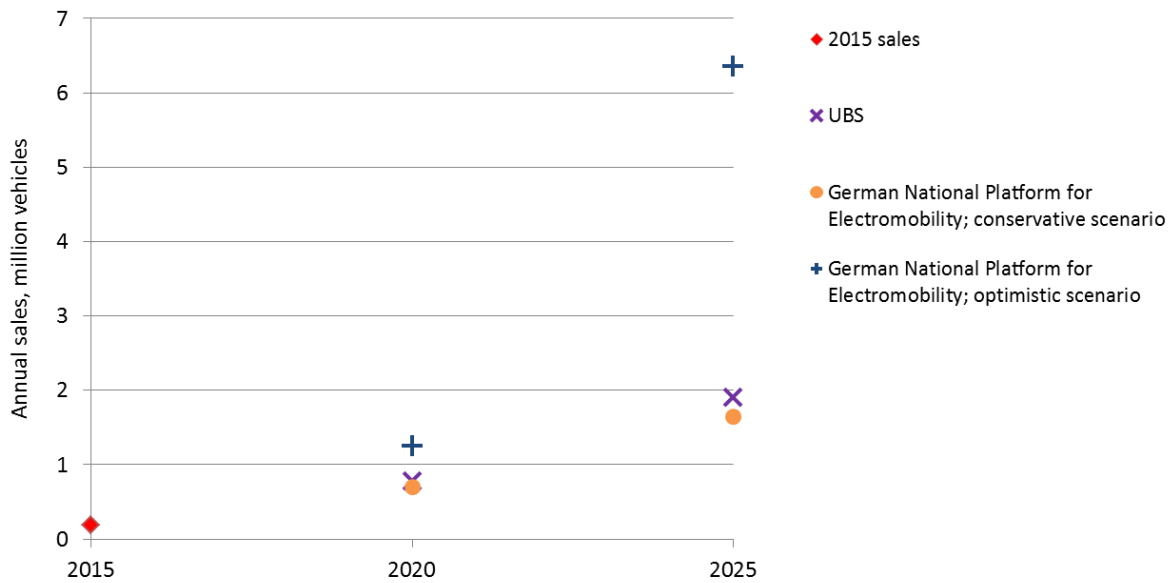


Figure 24: Projected European sales of new PHEV and BEV vehicles for 2015-2025. Source [34, 75, 90]

An important driver for OEMs to reduce GHG (greenhouse gas) emissions of their fleet is the requirements set by legislation in Europe as well as in Asia and US [53, 93-96]. Many OEMs have demonstrated their commitment to decarbonisation of road transport by developing new electric vehicle models in addition to alternative strategies which include optimization of the internal combustion engine (ICE) [97], reducing vehicle weight and development of fuel cell vehicles [98]. However, consumer demand, as recently shown by new players on the market (e.g. Tesla Model 3 early reservations) may soon become another important motivation for OEMs to launch competitive and high performance electrical vehicles on the market. Introduction of a new vehicle on the market is a massive, time-consuming R&I undertaking with a time to market for a new vehicle ranging between 4 to 7 years [8]. In a rapidly evolving global electrical vehicle market, automotive OEMs that are not quick to react to market trends and customer demands may lose their competitive edge. On the other hand great opportunities exist for OEMs that are willing and able to adapt and respond quickly to changes in this very dynamic market. In this sense the automotive market and customer base in Europe is not the same as that in the US, China or elsewhere. OEMs need to consider regional variations in driving expectations, infrastructure, economic affluence and government incentives that may affect consumer preferences and hence impact sales of new electric vehicle models (e.g. see the consumer view and expectations in the US [99]).

In this respect it is interesting to look at the upcoming models (2017-2020) announced by different OEMs, particularly for models with a foreseen price below \$ 50,000 and with

a reasonable driving range. When the exact vehicle price is not fully disclosed by OEMs, estimations based on similar/previous models are provided when possible. The realistic range in km is similarly provided. A list of upcoming BEV and PHEV models filed below, while not exhaustive, can reflect expected future trends in the automotive industry (see Table 6).

Table 6: Price and range of upcoming EV models (2017-2020) as announced by OEMs differentiated by region

		EU	US	JP	KR	CN
Brand	Model	Year of release	Price [\$]	Range [km]		
BMW	Updated BMWi3	2017	< 50,000	200		
Renault	Updated Zoe	2017	~ 35,000	300		
Daimler	Updated Smart ForTwo electric	2017	< 30,000	100		
Tesla	Model 3	2018	< 40,000	300		
GM	Chevrolet Bolt	2017	< 40,000	300		
Ford	Ford Focus Electric	2017	< 30,000	150		
Nissan	Nissan Leaf version 2017	2017	> 30,000	150		
Nissan	Nissan Leaf version 2018	2019	< 40,000	300		
Mitsubishi	eX SUV	2019	< 40,000	300		
Hyundai	Ioniq model BEV	2017	< 35,000	150		
Kia	Update of Soul Electric	2018	~ 35,000	150		
BYD	BYD Qin EV300 BEV model	2017	~ 35,000	240		

Among European OEMs, BMW is announcing a new strategy where a further advance in e-mobility is foreseen [100]. In 2017 a new version of the BMW i3 will be launched with a range of around 200 km [101] and its price is expected to be below \$ 50,000 [102]. Renault has announced delivery of a new version of the Renault ZOE in 2017, which will have a driving range of up to 300 km. The price, with the battery on sale option, should be around \$ 35,000 [103].

Daimler is investing more than €7 billion (\$B 7.9) in green technologies in the next two years alone. As part of this strategy Mercedes-Benz will expand its PHEV fleet (GLC Coupé 350 e 4MATIC, E 350 e, S 500 e) by 2018 [104], with all models priced well above \$ 50,000. Daimler will also launch a new Smart ForTwo electric vehicle in 2017 with a range of 100 km [105], whose price is expected to be well below \$ 30,000 [106].

Volkswagen has confirmed its strategy to launch over 20 additional electric vehicle models by 2020 but without disclosing concrete proposed models [60, 107]. Within the group, the brand Audi announced the launch, by 2018, of the first large-series battery-electric vehicle based on the PHEV Audi e-tron concept. The models, however, have not been released yet [61].

PSA Peugeot, Citroën and Dongfeng Group (CN) have strengthened their strategic partnership with the signing of a new agreement to design an electric version of the Common Modular Platform (CMP). This future electric platform (e-CMP) will deliver all-electric vehicles for the Peugeot, Citroën, DS and Dongfeng brands from 2019. However, no concrete model has been presented yet [57].

Outside Europe, other automotive OEMs are proposing several electric vehicle models to be launched in the next 2 - 3 years.

Tesla is anticipated to be the worldwide frontrunner with the launch of the Tesla Model 3 announced for 2018. It will be priced below \$ 40,000 with a driving range above 300 km [108].

Looking at other US OEMs, General Motors will launch the Chevrolet Bolt in 2017 which will also be priced below \$ 40,000 and with a driving range above 300 km [109]. Ford will not try to compete with the other two US OEMs in terms of driving range, but rather deliver lighter vehicles with a range of around 150 km at a more affordable price, estimated to be below \$ 30,000 (e.g. the new Ford Focus Electric to be launched in 2017) [110].

Among Japanese OEMs, Nissan is going to launch an updated version of Nissan Leaf in 2018-2019 with a driving range of 300 km and with a price estimated below \$ 40,000

[111]. Before then, the 2017 Nissan Leaf version, is expected to have a driving range of 150 km and a price above \$ 30,000 [112].

Toyota has been reluctant to take on board the full electric vehicle concept with its strategy focusing instead on HEV and PHEV for short-range, urban applications, and fuel cell electric vehicles for longer-range applications. However, with the steady arrival of competing battery-electric vehicles with ever increasing driving ranges (e.g. Chevrolet Bolt EV, Tesla Model 3), Toyota appears to be adjusting its thinking. They recently decided to establish an in-house venture company responsible for developing electric vehicles (EVs) by 2020 [113]. However, no concrete models are expected to be launched in the next 2 - 3 years, other than new update versions of their PHEV fleet [114]. Thereafter, by 2020, Toyota has announced plans to introduce a small, all-electric SUV [115].

Mitsubishi has announced the launch of the new eX SUV Concept in 2018-2019 with a range above 300 km and a price below \$ 40,000 [116].

South Korean OEMs, Hyundai and its sister company Kia, together have aggressive plans to become the world's second highest-volume maker of green cars by 2020, after Toyota. Although HEV and PHEV models will be a substantial part of this plan, full electric models are also foreseen. Hyundai is joining the race with a new all-electric SUV with 150 km range by 2018 [117], but price, pictures and previews are not available. Hyundai has also announced the launch in 2017 of the Ioniq model BEV with more than 150 km driving range and a price below \$ 35,000 [118]. Meanwhile Kia is preparing to launch a new version of its Kia Soul Electric BEV in 2018 with an improved driving range close to 150 km and expected price of around \$ 35,000 [119].

Chinese OEMs are much more linked to delivery to the domestic market. Looking at the top 20 PHEV and BEV sales in 2016 (up to October) on the Chinese market [75], the only non-Chinese electric vehicle model sold is the Tesla Model S (which ranks 17th). This trend is expected to remain at least until 2020 mainly due to the competitive prices of local models [120]. Most sales are expected to be low-speed models (as is currently the case e.g. Kandi Panda, and Zotye E-20/30 [89]) but also higher class vehicles, such as the new BEV version of the BYD Qin EV300 to be launched by 2017 with 240 km driving range and price around \$ 35,000 [70].

3.5.2 OEMs Tier 1 and Tier 2 supply chain

The growing electrical vehicle market may be a challenge also for the consolidated EU OEMs Tier 1 and Tier 2 supply chain industry, which has an annual revenue amounting to 1/3 of the EU OEMs industry. Electric vehicle manufacturers require suppliers of a range of new components for electric power train other than cells and battery packs. Such

components include connectors, cables, power electronics for controllers, converters and chargers, novel system integration services, innovative thermal management solutions and new light materials for the car body/frame such as aluminium or carbon fibre-reinforced polymers. OEMs need to build up a new set of suppliers for these products which changes the traditional group of Tier 1 and Tier 2 suppliers (which are mainly designing and producing parts for internal combustion engine powertrain such as pistons, camshafts, spark plugs, injection pumps, turbo chargers, fuel tanks, alternators, oil pumps, motor oils or manual and automatic gear boxes). The current status of Tier 1 OEM's suppliers shows a strong competitive position of EU companies with total revenue of B\$ 277 (see Table 7 and Figure 25). Besides that, their manufacturing capacity is globally distributed, since their production plants for parts are normally located in the proximity of OEM's vehicle assembling plants, which are also distributed around the globe. The degree of manufacturing delocalization can be quantified looking at the financials of the top 10 automotive suppliers with headquarters in Europe and North America, where it turns out that they generate 18% to 28% of revenues in Asia supplying OEMs with their products [121]. With a growing electrical vehicle market this picture may change substantially and this competitive position of EU Tier 1 industry may be challenged.

Geography (# suppliers)	Revenue 2014	Share 2014	Margin 2014	Revenue Growth 13/14	Profit Growth 13/14
Europe incl. UK (18)	277	42%	7,3%	7,9%	16,2%
thereof Germany (10)	178	27%	7,6%	9,1%	18,4%
Asia (11)	229	35%	6,4%	5,2%	20,1%
North America incl. Mexico (21)	153	23%	6,6%	7,3%	0,0%
Total (50)	659	100%	6,8%	6,8%	13,3%

Table 7: Geographical comparison of automotive suppliers' 2014 financial indicators (figures in US\$) [121]

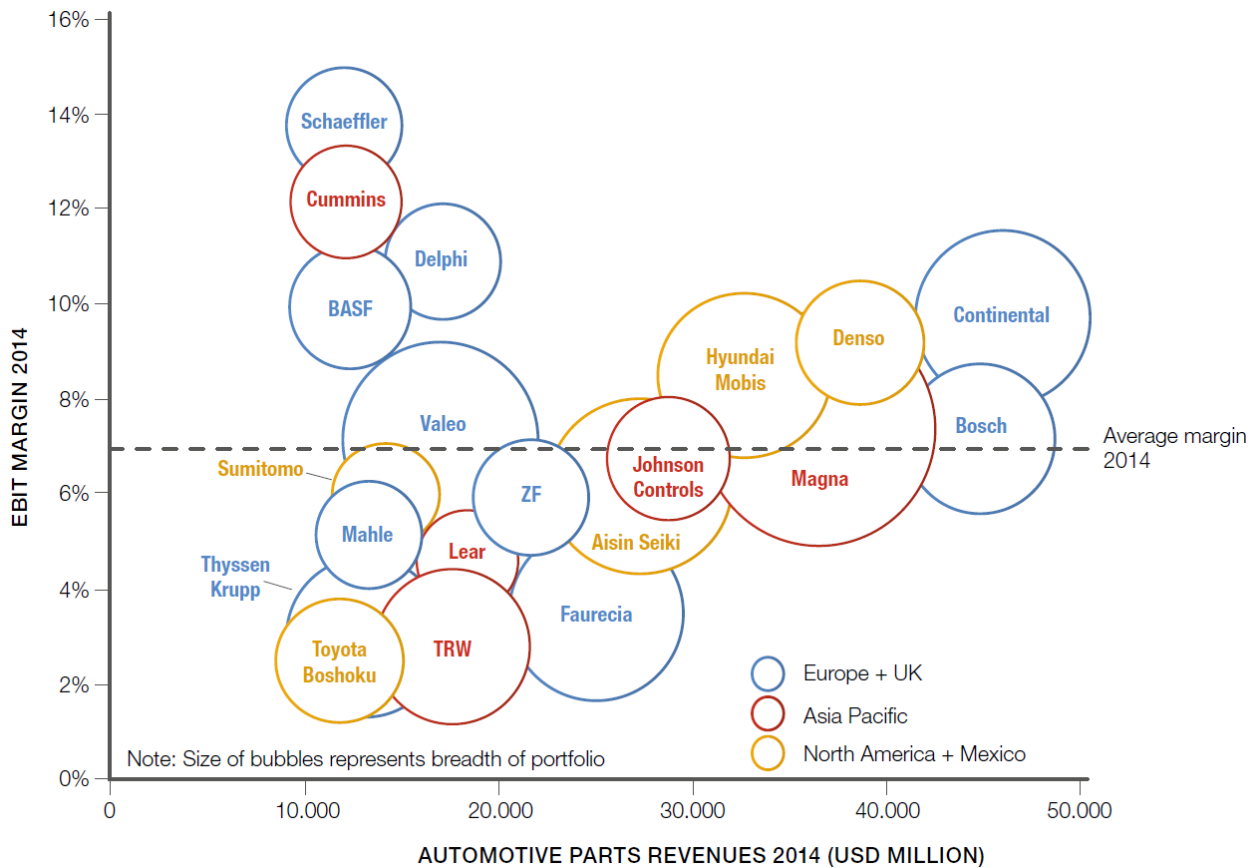


Figure 25: 4D analysis of top 20 automotive suppliers for EBIT margin (ratio of Earnings before Interest and Taxes to net revenue earned) and revenues (2014) [121]

The growing electrical vehicle market may create great opportunities for companies accepting risks and willing to invest. In this context, besides the traditional OEM's suppliers, new companies are also supplying the car manufacturers. Some traditional suppliers are investing heavily in a range of new technologies relevant to e-mobility (e.g. Continental (DE), Michelin (FR), ZF Friedrichshafen AG (DE)) or are looking to create joint ventures with established companies already active in the e-mobility sector (e.g. Bosch (DE)). Other companies, traditionally operating in the industrial sector are also becoming OEM's suppliers, such as companies active in the power electronic field (e.g. Semikron (DE), Mitsubishi (JP), Toshiba (JP) and Actia (FR)), or specialised in converter/charger products (e.g. BRUSA Elektronik (CH), EDN GROUP (IT)), cable and connectors (e.g. Lapp Holding AG (DE), Lem Holding SA (CH)) and electric engines (e.g. Yasa Motors (UK), Sram Technology (IT), BorgWarner (USA)). Similarly companies, who traditionally supply the aerospace and military industry and who have already developed suitable products and services for e-mobility (e.g. BAE Systems (UK), Ricardo (UK)) are breaking into the OEM supply market. In addition there are also companies providing consulting services for system integration (e.g. AVL (AT), Lenze Schmidhauser (CH)).

3.6 Recycling

Due to the constantly increasing significance of lithium ion batteries, especially in the growing automotive and energy storage sectors, recycling processes and related issues are highly relevant for the EU circular economy package [122]. Greater recycling of waste batteries and increased re-use or second use will bring benefits for both the environment and the economy by boosting business and reducing waste. Increased recycling will also mitigate the dependence on certain critical materials, such as cobalt.

The Circular Economy Strategy is related to the transfer of the Extended Producer Responsibility (EPR) and to the End-of-Waste status. The EPR concept is aimed at promoting the integration of environmental costs associated with goods throughout their life cycles into the market price of the products. The EU has issued a number of directives aimed at increasing producer responsibility, including the EU Battery Directive (Directive 2006/66/EC) [9] that introduces the EPR for battery waste. The directive enforces battery producers, or third parties acting on their behalf, to finance the net cost of collecting, treating and recycling waste batteries. However, the Directive needs to consider the specificities of lithium-ion traction batteries in the absence of guidelines on the transfer of ownership and changes to EPR with corresponding identification of responsibilities for a second use option. In addition the Battery Directive needs to be harmonized with Directive 2000/53/EC on end-of-life vehicles and with Directive 2008/98/EC on waste (Waste Framework Directive).

Recycling of lithium-ion batteries is a complex and costly process hindered by the absence of a standardised product across the lithium ion battery market which, as a result, has a wide variety of chemistries and battery formats. Furthermore, additional complexities arise from the need for dismantling and pre-treatment of large electric vehicle batteries to reach sizes compatible with recycling process. A comprehensive overview of various steps in recycling processes is given in [22, 123, 124]. Four types of recycling technologies exist [22]:

- a) mechanical
- b) pyrometallurgical
- c) hydrometallurgical
- d) thermal pre-treatment followed by hydrometallurgical method (often also called a combination of pyrometallurgical and hydrometallurgical methods)

Mechanical treatment includes crushing and physical separation of components and recovery of the black mass, which contains valuable metals such as cobalt, nickel, manganese, lithium etc. [22].

In pyrometallurgical processes spent Li-ion cells are processed at high temperature without any mechanical pre-treatment as batteries are loaded into the furnace directly. This class of recycling process recovers cobalt, nickel, copper and iron in form of a metal alloy. Metals such as aluminium, manganese, and lithium are lost in the slag and plastic and other organic components are incinerated [22].

Hydrometallurgical methods include mechanical pre-treatment and metal recovery from the black mass by means of leaching, precipitation, solvent extraction, ion-exchange resins and bioleaching [22, 123]. In addition to cobalt, nickel, copper and iron, hydrometallurgical processes enable recovery of lithium with high purity.

A hydrometallurgical process is often preceded by a thermal pre-treatment step (type d) to remove organic compounds and graphite which adversely affect leaching and solid-liquid separation steps of the recycling process [22].

At present the main focus in recycling of Li-ion batteries is the recovery of cobalt since this metal has a high economic value and is a critical raw material for the EU [22]. The recycling rate of lithium from end-of-life products, including batteries, is currently below 1% according to the International Resources Panel [125]. Nevertheless, recovery of less economically valuable metals, including lithium, may become viable in future [22]. Therefore, R&I needs exist for improving the cost effectiveness of the recycling processes and development of more efficient recycling processes.

The efficiency of battery recycling is a combination of two factors: collection rate and recycling efficiency. Collection rate expresses the fraction of produced lithium ion batteries that are collected at their end-of-life, while recycling efficiency is expressed as the weight percentage of metals, metal compounds, plastics, and other products recovered from the collected waste that can be directly reused in battery production or in other applications or processes. Recycling efficiency is considered a key parameter for assessing the quality of recycling however a methodology is not yet standardized for its calculation. Pre-normative research to develop standards and guidelines for collection and transportation of used batteries as well as standards and guidelines for battery second-use are needed.

Efficiency of recycling for various elements in selected processes in terms of % recovery of different material are compared in Table 8.

Table 8: Efficiency of recycling for various elements in selected processes for NMC and LFP chemistries [75]

Material	Combination of pyrometallurgical & 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

At present recycling of lithium ion batteries is mainly limited to portable batteries since still there are no big volumes of waste electric vehicle battery that have reached their end-of-life. Spent Li-ion batteries are recycled industrially in many regions of the world. An overview of recycling companies and their processes is given in Table 9. Data was compiled from various sources and, where possible, cross-checked with information on the websites of the listed companies or by contacting listed companies directly.

Table 9. Li-ion battery recycling companies, processes and capacity. [22, 123, 124, 126, 127]

Company (HQ location)	Recycling facility location	Battery types	Process	Recycling volume, tons of batteries per year
<i>Europe</i>				
Umicore Battery Recycling (BE)	Hoboken (BE)	Li-ion, NiMH	P	7000*
Accurec Recycling GmbH (DE)	Mülheim (DE)	NiCd, NiMH	P with H treatment of	1500-2000
	Krefeld (DE)	Li-ion		

			the slag and fluoride dust	6000*
Glencore (formerly XStrata) (CH)	Sudbury (CA) Rouyn-Noranda (CA) Kristiansand (NO)	Li-ion	P with H treatment of the slag and electrowinning	7000*
Recupyl S.A. (FR)	Grenoble (FR) Singapore (SG)	Li-ion	H	110*
AEA Technology (UK)	Sutherland (UK)	Li-ion	H	
SNAM (FR)	Saint Quentin Fallavier (FR)	NiCd, NiMH, Li-ion	P+ mechanical separation + H to extract Co and Ni	300*
AkkuSer Oy (FI)	Nivala (FI)	NiCd, NiMH, Li-ion, Zn alkaline	mechanical	1000 (Li-ion) 4000*
Batrec Industrie AG (CH)	Wimmis (CH)	Li	P + mechanical treatment	200*
Euro Dieuze / SARP (FR)	Dieuze (FR)	Li-ion	H	200*
Valdi (ERAMET) (FR)	Commentry (FR)	Various including Li-ion	P	20000* (from 2017)
G&P Batteries (UK)	Darlaston (UK)	Various including Li-ion		
North America				
Retriev Technologies Inc.	Trail, BC (CA) Baltimore, OH	Li metal, Li-ion	H	4500*

(CA)	(US) Anaheim, CA (US)			
AERC Recycling Solutions (US)	Allentown, PA (US) West Melbourne, FL (US) Richmond, VA (US)	All types, including Li-ion and Li metal	P	
Japan				
Sony Electronics Inc. - Sumitomo Metals and Mining Co. (JP)		Li-ion	P	120-150
Nippon Recycle Center Corp. (JP)	Osaka (JP) Aichi (JP) Miyagi (JP)	Ni-Cd, NiMH, Li-ion, alkaline	P	
Dowa Eco-System Co. Ltd. (JP)		Various including Li-ion	P	1000*
JX Nippon Mining and Metals Co.		Various including Li-ion	P	5000*
China				
Shenzhen Green Eco-manufacturer Hi-Tech Co. (GEM) (CN)	Jingmen, Hubei (CN)	NiMH, Li-ion	H	20000-30000*
Hunan BRUNP (CN)	Ningxiang, Changsha, Hunan (CN)	Various including NiMH and Li-ion	H	3600-10000* >6000

*P – pyrometallurgical process; H- hydrometallurgical process; * recycling capacity of the facility*

In Europe companies such as Umicore (BE) and Recupyl (FR) active for several years in the battery recycling sector have developed their own recycling processes. Umicore has developed a so-called "Umicore process", an ultrahigh temperature pyrometallurgical process, and runs a facility in Belgium with an annual capacity of 7000 tons of batteries [21]. Recupyl patented a hydrometallurgical recycling process, which has a higher material recycling efficiency (see Table 8). Accurec Recycling GmbH runs a facility Krefeld (DE) recycling 1500-2000 tons of spent Li-ion batteries [22, 128]. Their annual capacity for disassembly and subsequent recycling of Li-ion automotive batteries is more than 600 tons [128]. Valdi (FR), a ERAMET Group subsidiary, has transferred its battery recycling facility from Le Palais-sur-Vienne (FR) to Commentry (FR), where batteries will be recycled through a dedicated pyrometallurgical process [129]. The unit will recover 100% of metal content, enabling it to achieve a recycling efficiency target of 65%, above the minimum requirement of 50%, stipulated by the EU Batteries Directive (Directive 2006/66/EC) [129]. From 2017, Valdi will have annual processing capacity of 20,000 tons of batteries [130]. AkkuSer Oy (FI) operates a battery recycling facility in Nivala (FI), where Ni-Cd, NiMH, lead accumulators, alkaline batteries and Li-ion batteries are mechanically recycled in a so-called Dry-Technology[®] process [22, 131]. Annually about 1000 tons of spent Li-ion batteries, coming from the European market, are processed at this facility [22].

In the United States, there is no federal law governing EPR, and each state may choose to implement its own policy and laws. California, for example, is pioneering a process for waste regulation [132], but so far only portable batteries are considered and California lacks the infrastructure to manage the forecasted volume of EV lithium ion batteries at their end-of-life [133]. Since 1996, a voluntary programme called Call2Recycle, which is funded by electronics manufacturers, has recycled more than 38.5 million kilograms of small consumer batteries and mobile phones in the US and Canada, but this is still just a tiny fraction of the total [134]. In Canada provinces of British Columbia, Quebec and Manitoba have a mandatory recycling programme, and in these places, Call2Recycle collects about 25% of what is sold [134]. Retriev Technologies Inc. (former Toxco Inc.), which has developed its own hydrometallurgical process, is a leading battery recycling company in Canada and the US. Over the past 20 years, Retriev has processed more than 10,000 tons of lithium ion batteries. Retriev is researching a new recycling method for Li-ion batteries called "direct recovery", originally developed by OnTo Technology, a research and development company in Bend, (Oregon, USA) [134]. As explained in [134]: "Rather than recovering basic elements, as with pyrometallurgy, or partially breaking down the molecular structure of compounds, as with hydrometallurgy, this method involves bathing the cathode in a soft chemical solution to rejuvenate it". It is a low-temperature, low-energy, low-emissions process with very limited waste. Recycling

using this process is also significantly cheaper compared to conventional pyro- and hydrometallurgical processes [134]. Most of the cost savings come from not having to rebuild the cathode again as materials are retained in their battery-ready state and since direct recovery uses less energy than conventional methods [134].

Looking at the Asian region, Japan has a legislation requirement for batteries similar to the EU [135]. Japan Portable Rechargeable Battery Recycle Center (JBRC), non-profit organization, provides used battery collection boxes across the country. Companies such as Sony and Nippon Recycle Center Corporation are contracted to receive these batteries for recycling. There are also contracts directly with companies to collect and recycle their end-of-life batteries as well as battery production scrap material [136].

In China there is currently a shortage of appropriate policies and collection systems for batteries despite of a growing community concern about the impact of waste lithium ion batteries on the environment and public health. Industry is increasingly expected to report on and be accountable for the waste their products generate. Furthermore the criticality of some raw materials, such as nickel and cobalt, puts more pressure on manufacturers and government to properly address battery recycling. Therefore, appropriate policies and collection systems for batteries in China need to be defined, and recycling infrastructure also needs to be developed [137]. Some Chinese companies are active in the battery recycling business such as GEM Jingmen and BRUNP Hunan. GEM has an annual disposal capacity of waste batteries and Co and Ni scrap of about 30,000 tons, with an annual production of recycled cobalt and nickel more than 3300 tons [137]. A facility of BRUNP Hunan has a total designed processing capacity of 10,000 tons per year.

4 Conclusions

This report has gathered data on the automotive traction battery value chain with a view to underpin decisions where European R&I investments are needed, considering where these can create opportunities to boost European competitiveness in the automotive battery sector. On the basis of this data a number of opportunities for increased R&I support in specific areas of the automotive battery value chain, which may help achieve the objective for increased European competitiveness in this sector, have been identified and are highlighted below.

OEMs are facing increasingly stringent emission targets and they will need to consider greater investment in efficient powertrain technologies going beyond optimization of the internal combustion engine. Furthermore, OEMs are looking at evolving consumer purchasing behaviour and electrical vehicle acceptance which may soon become relevant in global sales. How European OEMs will adjust their strategies varies, however a growing electrical vehicle market may justify growing R&I effort to support a competitive domestic manufacturing in relevant segments of the value chain including cells for use in vehicle battery packs.

The information provided in this report shows that EU industry has some production base in all segments of the battery value chain, but it is far from being self-sufficient. In the raw and processed materials, cell component and cell manufacturing value chain segments Europe holds a minor share of the market, whereas in the pack and vehicle manufacturing and recycling segments Europe is among the market leaders. Within the car manufacturing segment, EU industry is expected to maintain its position also for EV production.

European OEMs and their Tier 1 and Tier 2 suppliers need to be prepared to satisfy the future demand for electric vehicles as projections for global electrical vehicle sales up to 2040 show an increase in demand. Many European Tier 1 and Tier 2 automotive OEM supply industries, currently serving the ICE market, are demonstrating their ability to adapt and respond to new opportunities presented by the growing electrical vehicle market. This flexibility should be supported given the dynamic needs of their OEM customers many of whom are still developing their own strategy on what part of pack manufacturing to outsource.

Support to R&I in this sector can help existing and new Tier 1 and Tier 2 industries innovate and increase their flexibility and hence maintain a competitive edge.

In the recent past the numbers of EV sales did not meet the anticipated level and for the majority of European OEMs, this may have been one reason not to start and sustain private investments in competitive domestic cell manufacturing.

Another factor which has discouraged large scale European cell manufacturing, and which is often cited by car manufacturers, is the current global cell manufacturing overcapacity. Nevertheless, looking to the future, the current over-capacity in itself should not preclude investments in this area since projections for large penetration of EV indicate that automotive lithium-ion cell demand and supply may soon be matched (by around 2020).

To become competitive in this time frame however, consolidated R&I action at a European level is required in the short term to secure Europe's strong industrial position in pack manufacturing in the future.

Current projections indicate a research trend to develop improved (e.g. higher voltage) cells for automotive use based on conventional Li-ion chemistries such as NMC and LFP. The general approach being adopted is to develop advanced materials (e.g. silicon enriched anode, solid state electrolytes) rather than developing new chemistries, at least until 2025. These improved technologies are speculated to transition by 2030 towards post Li-ion technologies (Li-air, Li-S, Na-ion) once their performance is proven in automotive applications. Li-ion technology is therefore expected to remain as the dominant deployed technology at least until 2025 - 2030.

R&I investments in improved contemporary chemistries, from materials up to large scale cell manufacturing capabilities, are needed to satisfy the current incremental performance improvements needed.

Similar R&I investments are needed for post-lithium ion chemistries to allow sufficient time for their development and subsequent translation into a manufacturing process to realise significant improvements in performance.

Failure to invest the necessary resources in this way will only prolong and exaggerate Europe's historical deficit in competitive cell manufacturing which may also threaten Europe's knowledge base which has the tendency to move where production sites are located.

Secure access to materials used in cell manufacture is a fundamental prerequisite if Europe is to become competitive in this segment. Issues associated with access and use

of critical materials for cell production can be addressed by (i) tapping new sources of critical materials, (ii) substituting critical materials with less critical ones and (iii) recycling/reuse of critical materials.

R&I support to develop new mining/extraction techniques may alleviate potential supply concerns for materials where reserves are located outside the EU territories.

R&I on alternative Li-ion chemistries, made of more accessible raw materials, could cover development of alternative chemistries to alleviate the need for the critical materials, cobalt and natural graphite.

With regard to lithium, projections suggest that reserves are sufficient to satisfy the increase in demand brought about by increased use of batteries for automotive purposes. Benefits gained from mitigating dependence on critical materials will not be limited to the raw material sector but, and maybe most importantly, can enhance opportunities for the EU industry to break the foreign monopoly in the cell manufacturing sector by substitution of materials.

A sector where EU industry has a strong and dominant position is in the battery recycling part of the value chain. EU pioneering legislation in this area has made it possible to develop a well-structured industry. Recycling also helps alleviate concerns on the security of supply of critical raw materials used in batteries. However the battery recycling sector is currently struggling to prepare for increased volumes of battery waste expected from the automotive traction sector.

R&I needs exist for improving the cost effectiveness of the recycling processes, development of more efficient processes, pre-normative research to develop standards and guidelines for collection and transportation of used batteries as well as standards and guidelines for battery second-use.

Opportunities for increased European R&I support in areas other than those identified in this report may also exist including battery R&I for applications other than automotive. When pursued, targeted and strategic R&I efforts should be performed in an integrated approach to leverage the knowledge generated in a cost-effective and innovation-enhancing manner.

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List of abbreviations and definitions

LCO	Lithium Cobalt Oxide – Cathode Material
NMC	Nickel Manganese Cobalt Oxide – Cathode Material
NCA	Nickel Cobalt Aluminium Oxide – Cathode Material
LFP	Lithium Iron Phosphate - Cathode Material
LMO	Lithium Manganese Oxide (spinel) – Cathode Material
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
ICE	Internal Combustion Engine
CAGR	Compound Annual Growth Rate
GWh	Giga Watt Hour
kWh	Kilo Watt Hour
ESS	Energy Stationary Storage
GHG	Green House Gases
LME	Lithium Metal Equivalent
LCE	Lithium Carbonate Equivalent
EPR	Extended Producer Responsibility
US	United States
KR	South Korea
JP	Japan
EU	European Union
CN	China
CH	Switzerland
DE	Germany
FR	France
NL	The Netherlands
BE	Belgium
IT	Italy

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