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EU Competitiveness in Advanced Li-ion Batteries for E-Mobility and Stationary Storage Applications – Opportunities and Actions

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Title: EU Competitiveness in Advanced Batteries for E-Mobility and Stationary Storage Applications – Opportunities and Action

Abstract
Projected global demand for Li-ion batteries for mobility and stationary storage applications will exceed currently available and known planned production capacities already in the near future. Conditions for establishing a globally competitive Li-ion battery value chain in the EU are identified and enabling measures that the Commission can deploy are proposed.

Contents

Executive summary

This JRC Science for Policy Report focuses on competitiveness aspects related to batteries as a key enabling technology for electric mobility and stationary storage. The report fits within the overall JRC effort aimed at addressing European industrial competitiveness as outlined in the Clean Energy Package [1] and serves as input to the definition of the overall Enabling Framework for the Energy Union.

Following an introduction, the document reviews recent cost and market evolution of Lithium-ion battery (LIB) cells (chapter 2 and 3 resp.), focussing on e-mobility and stationary energy storage applications. This is followed by an overview of current and announced global capabilities for large-volume manufacturing of LIB cells in terms of capacity and geographical location (chapter 4). Chapter 5 lists opportunities for the EU to become competitive in LIB manufacturing and is followed by an overview of investment costs related to the establishment of industrial LIB cell manufacturing facilities (chapter 6). Chapter 7 provides available data on job creation potential associated to establishing LIB manufacturing capacities. Finally, chapter 8 identifies the conditions that have to be fulfilled for establishing a globally competitive LIB cell manufacturing chain in the EU, additional factors that can support the business case, and suggests measures that the Commission can take to support their realisation and thereby enable EU industry to take its share in a globally booming market.

1 Introduction

This JRC Science for Policy Report builds upon the JRC Science for Policy Report *Li-ion battery value chain and related opportunities for Europe* [2] issued in December 2016 by providing updates on LIB deployment estimates for electric vehicle applications (xEV: BEV, PHEV, HEV), as well as extending its scope to include LIB for stationary energy storage (ES) applications. The report elaborates further on the potential of and suggests the measures that need to be implemented for achieving a globally competitive LIB cell manufacturing industry in the EU.

The cost of and domestic capacity to manufacture LIB cells and battery pack systems have a direct impact on the EU's ability to compete with the global market leaders in this sector. Cost and manufacturing targets with a time horizon up to 2030 were agreed in 2016 between EU industry, Member States and the Commission. These targets are enshrined in a Declaration of Intent (DoI) on batteries for e-mobility and stationary storage applications [3] which has been prepared in the frame of the Integrated SET-Plan [4]. Accordingly, and because of the relevance of manufacturing cost and capacity to EU competitiveness in the battery sector, these targets are considered in this document.

While LIB performance in the two major application areas of xEVs and ES is a decisive factor for their large-scale deployment, battery performance and related targets are not considered explicitly in this document. This does not eclipse their importance to competitiveness since the performance and safety of any advanced European battery technology in any application will need to be as good as, if not better than, those of competing incumbent technologies. High performance and safety are a prerequisite to competitiveness and therefore considered a given in the following discussion.

2 Cost evolution of LIBs

Recent cost evolution (past and projected) of LIB [a] is illustrated in Figures 1 and 2. Annex I provides background information on methodologies used for cost projections and on the sometimes (quite) different results obtained from their application.

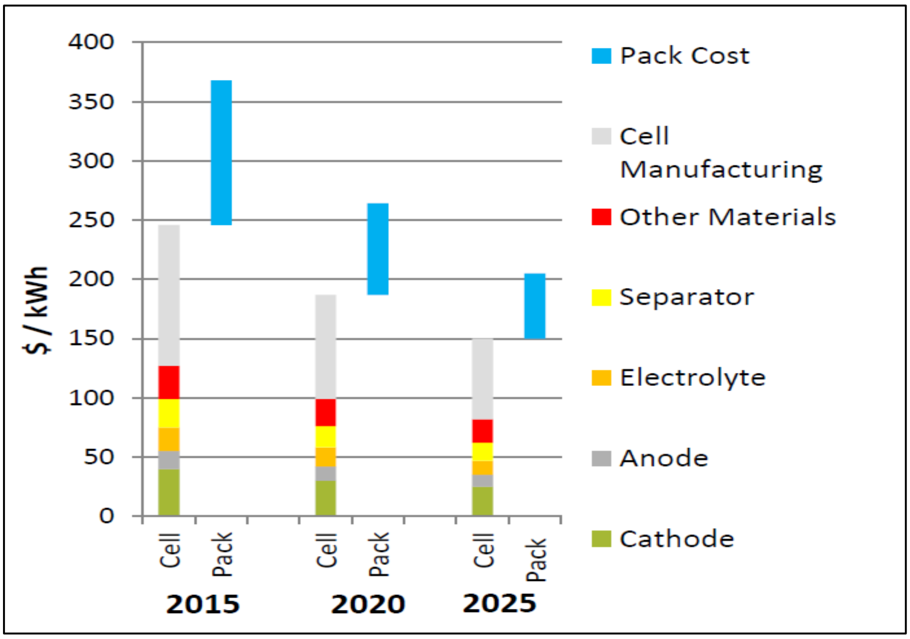


Figure 1: Evolution of LIB component, cell and pack costs for EV applications [5].

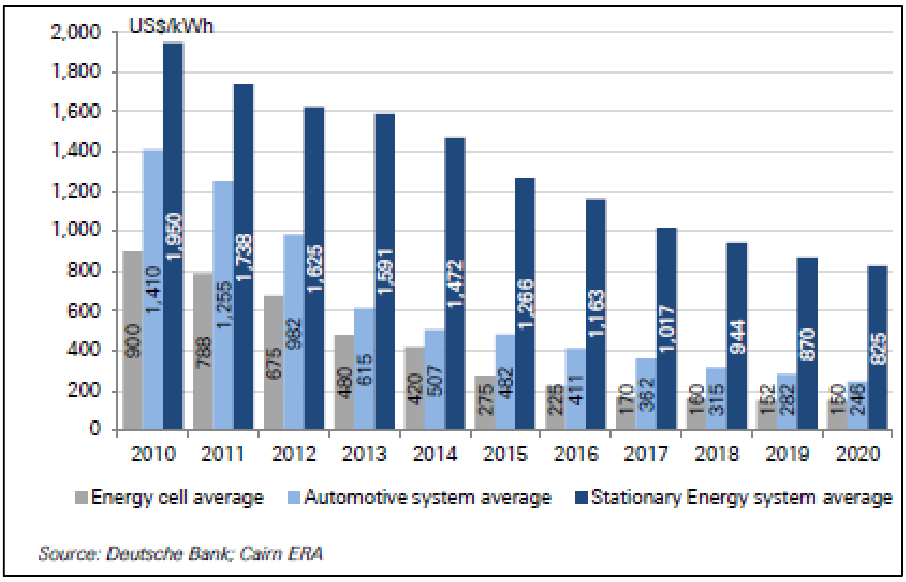


Figure 2: Evolution of LIB cell and system costs for EV and stationary storage application [6].

[a] Studies on battery costs do not always differentiate between cell, pack and system level. This is one of the reasons why quite different numbers for "battery costs" appear in the literature; other reasons are discussed in Annex I.

It should be noted that some sources already now indicate lower costs for LIB cells than those shown in Figs. 1 and 2 (or imply lower cell costs because of claimed lower pack costs):

- EV battery cell prices <200€/kWh for OEMs [7]
- Audi buys batteries at $114/kWh cell price [8]
- General Motors paying $145/kWh for the LIB of Chevy Bolt [9]
- lithium-ion-batteries selling for under $140/kWh [10]

This indicates that cost targets for packs in the DoI of 90 €/kWh in 2022 and 75 €/kWh in 2030 for EV and of 150 €/kWh for ES by 2030 are feasible (see also Fig. I.3 in Annex I).

Two main causes can be discerned for the drastic cost decreases shown in Figs. 1 and 2:

- steady improvement of battery performance (primarily energy density) through sustained R&D aimed at improving materials, reducing the amount of non-active materials, reducing the cost of materials, improving cell design, increasing production speed and improving production yield. This has resulted in lower costs at both cell level and battery pack level.
- increased production volumes, particularly in China, bring economy of scale to lithium-ion battery manufacturing. According to [5], LIB global manufacturing investments in the period 2011-2014 exceeded 10-12 B$ for 50 GWh additional capacity, leading to an average specific investment cost of $250/kWh. In the period 2014-2017 average specific investment costs decreased to $150/kWh.

The effect of production volume on cost of LIB packs (2015 figures) is shown in Fig. 3 which indicates a levelling-off of pack cost towards $175/kWh for BEV batteries for production volumes exceeding 200,000 packs/year [11][b]. This pack level cost is reported to be equivalent with a LIB cell cost of $100/kWh, which is widely considered by battery experts to trigger acceleration of storage technologies uptake, both for e-mobility and for stationary applications. Such a cost is deemed achievable by 2025 or by 2030 at the very latest [12, 13, Annex I] and may lead to a situation where global demand for LIB cells outpaces production capacity available at that time (see chapter 4). In fact, an acceleration of the uptake of xEVs has most recently been forecasted to occur even earlier, particularly in Europe, as of 2020 onwards [12].

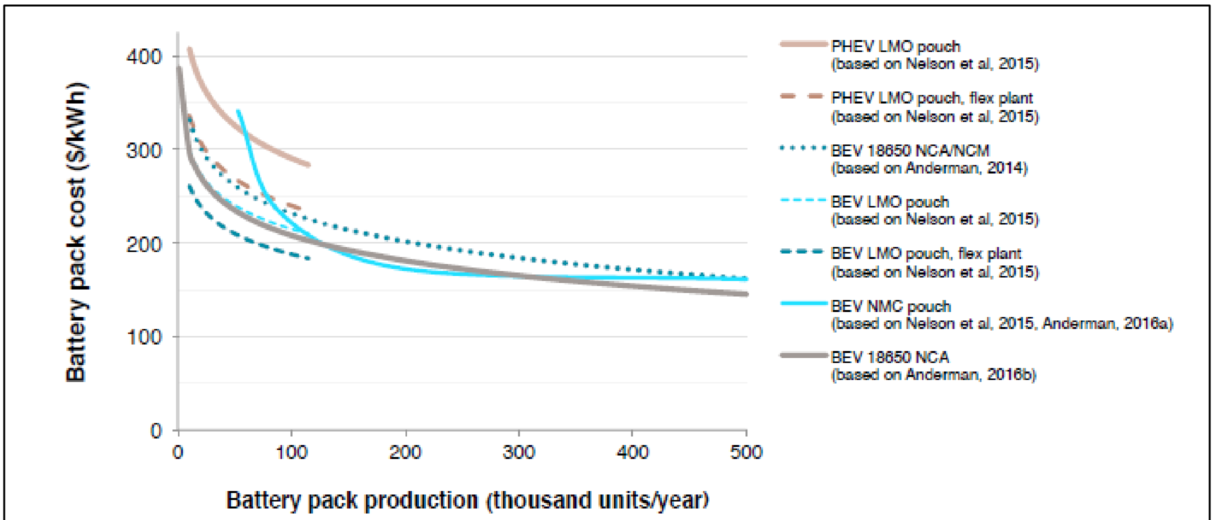


Figure 3: Dependence of LIB pack cost for xEV on production volume [11].

[b] See considerations in Annex I on costs levelling-off.

The evolution in the ratio between LIB cell and pack/system costs for EVs shown in Figs. 1 and 2 is expected to be affected by the degree of vertical integration[c] along the battery value chain. This is mainly because products in the segments upstream of cell manufacturing (see chapter 5) represent commodities in a cost-driven world market, whereas downstream from cell manufacturing they depend on the application and are therefore value-driven. Enhanced vertical integration – as expected in the mega/gigafactories currently being planned (see chapter 4) – is expected to decrease the cost ratio between LIB packs and cells.

The lower degree of vertical integration along the production chain explains why LIBs for energy storage applications have not fully realised the same economies of scale as for EV applications (Fig. 2 and Fig. I.1 in Annex I). Whereas energy storage costs have dropped considerably and will continue to fall, they are expected to continue to lag cost development in the xEV market, which has first-mover advantage in a currently larger volume market (see chapter 3).

When interpreting technology cost reductions as presented in Figs. 1, 2, 3 above, it should be realised that the cost of application of the considered technology[d], and hence its competitive position versus incumbent technologies, is additionally affected by technical performance parameters, such as e.g. technology lifetime, efficiency, etc.

Take-Away #1:

> The costs of LIBs continuously decrease and will soon reach a level that triggers their wide-spread, accelerated deployment in xEVs and ES applications.

[c] Vertical integration is the combination in one company of two or more stages of production normally operated by separate firms, aimed at reducing costs by decreasing transportation expenses and turnaround time.

[d] known as the application-specific levelised cost

3 Markets for LIBs

Current and projected annual global market forecasts for LIB from a number of recent sources [5,6,14,15,16,17,18] are summarised in the table below (market values are expressed at cell level):

	Market (GWh)			Value (B$)			notes
	2016	2020	2025	2016	2020	2025	
All applications	78	130-250	210-535	18.5-20.6	28-48	36-88	Consumer products, power tools, e-mobility, energy storage
Growth factor compared to 2016		**2.3** (1.7-3.2)	**4.3** (2.7-6.8)		**1.9** (1.4-2.6)	**2.9** (1.7-4.8)	
xEV[e, f]	33	60-116	105-300	7.5-9.5	12-34	16-63	LDV + buses, >50% in China alone
Growth factor		**2.5** (1.8-3.5)	**5.4** (3.2-9.1)		**2.4** (1.3-4.5)	**3.8** (1.7-8.4)	
Non-automotive (excl. consumer)	0.3	1.4	6.2	0.2	1.2	4.5	by 2025 50% marine
Growth factor		**4.8**	**20.7**		**6.0**	**22.5**	
ES	1.5-4.7	9-18	17-48	0.5-1.3	2.5-6	4-10	LIB technology assumed to increase from 70% (2016) to >95% (2020 and beyond) of all new installed capacity; 2nd use not considered
Growth factor		**4.8** (1.9-12.)	**11** (3.6-32)		**4.8** (1.9-12)	**7.8** (3.1-20)	

Table 1: Global market forecasts and increase factors in terms of size and monetary value for different applications of LIBs [sources as indicated in text].

[e] Market volume numbers for xEV consider the scenarios for xEV (BEV, PHEV, HEV) deployment numbers as well as the evolution in battery capacity needed for the different types of xEV.

[f] The numbers for xEV in 2025 in [12] are considerably higher because of the forecasted earlier mass uptake: 256-1331 GWh, corresponding to 23-120 B$. Similarly, [13] forecasts 408 GWh capacity for EVs (light duty vehicles only) in 2025 and 1.3 TWh in 2030, and 81 GWh ES in 2024.

Fig. 4 shows that the largest global deployment share of LIB till 2025 will be in xEV, whereas deployment of LIB for ES, while starting from a smaller base, is projected to be approximately twice faster than for xEV applications throughout the considered period (Fig. 5).

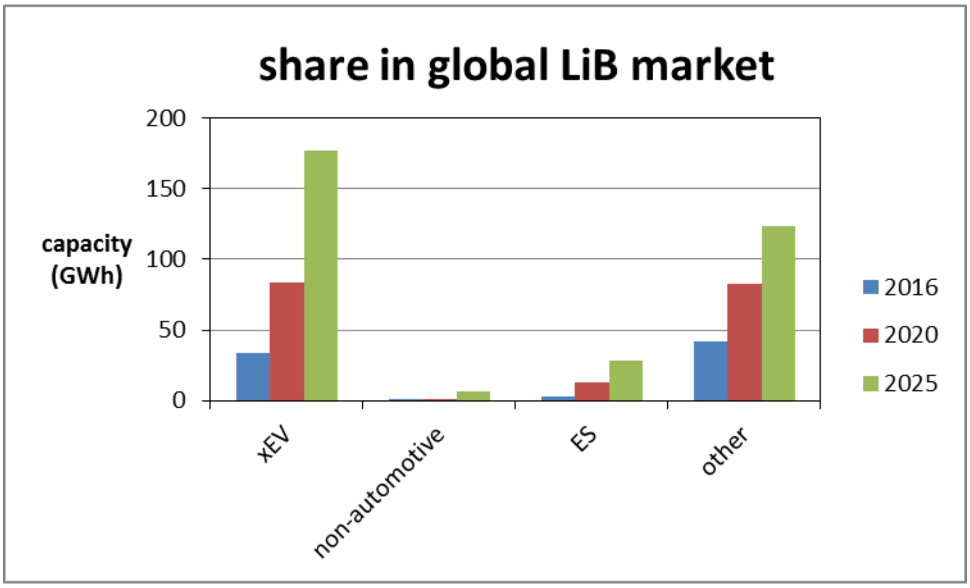


Figure 4: Share of different applications of the total global market for LIB [average estimates from sources used for Table 1].

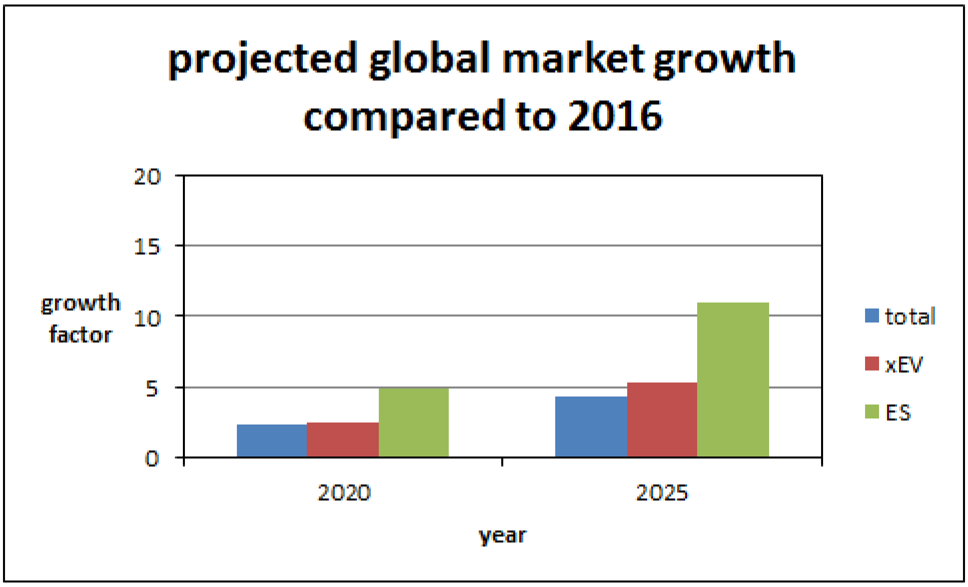


Figure 5: Growth factor (in terms of GWh(20xx)/GWh(2016)) for global LIB deployment in different applications [median values from Table 1].

Market forecast numbers for xEV in Europe range from 14 to 24 GWh in 2020 and from 37 to 117 GWh in 2025, with the lower estimate corresponding to a conservative scenario and the higher estimate to an optimistic scenario) [19]. The forecast average corresponds to around 22% of the global xEV market in 2020, increasing to around 35% in 2025[9].

[9] Not considering the forecasted earlier mass uptake of xEVs in [12] and [13].

Market forecasts for batteries for ES applications in Europe are given in [20], starting from an installed capacity in 2016 of 5.3 GW, increasing to 7.6-9.8 GW in 2020 and 11.5-14.5 GW in 2025. These numbers, in unit of power (GW) instead of energy (GWh)[h], indicate growth factors of 1.6 till 2020 and of 2.5 till 2025. A number of reasons may explain the difference with the increase factors shown for ES applications globally in Fig. 5: deployment number and type of storage facilities, share of LIB in battery storage facilities, etc.

Take-Away #2:

> The global market for LIBs in xEV and ES applications is huge. xEVs will represent the largest market in the near future, whereas expected growth rates are highest for ES applications. Most recent market forecasts for both applications are being revised upwards.

[h] The power capacity (GW) of storage cannot directly be translated into energy capacity (GWh) because this depends on the discharge time and the number of charge-discharge cycles.

4 LIB cell manufacturing capacity

In 2015 the world's total LIB cell manufacturing capacity amounted to 60 GWh and was primarily located in China, Japan, and Korea [2]. Together, these countries hosted 88% of total global LIB cell manufacturing capacity for all end-use applications. Asian countries were also home to a significant share of the LIB-specific materials global manufacturing capacity in 2015: cathodes (85%), anodes (97%), separators (84%), and electrolytes (64%). This concentration of cell manufacturing capacity and upstream supply chains contributes to LIB industrial clusters in each of these countries [2], which strengthens their competitive position vis-à-vis the rest of the world, through vertical integration or through joint ventures covering successive segments in the production chain up to and including cell manufacturing.

The global dominance of Asian LIB cell manufacturers is also reflected in the trade of LIB materials and cells [21]. Fig. 6 (left) shows the positive trade balance of Asian producers and the negative trade balance for other world regions in 2014 for LIB cells for all applications. The right hand side illustrates the magnitude of trade flows between countries[i].

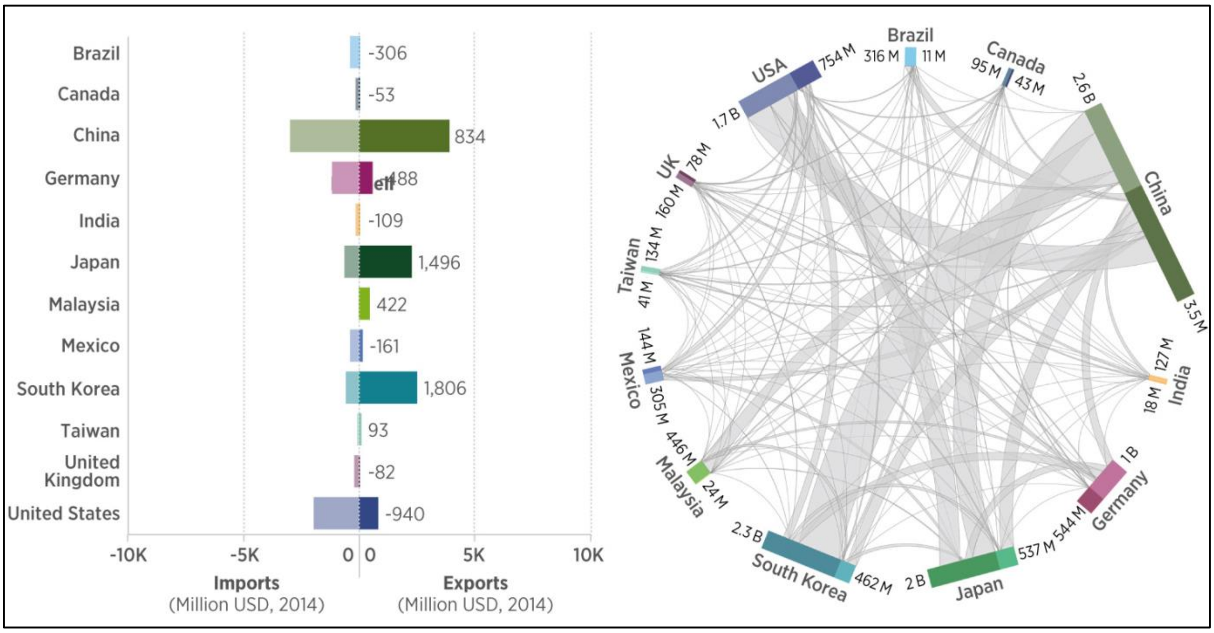
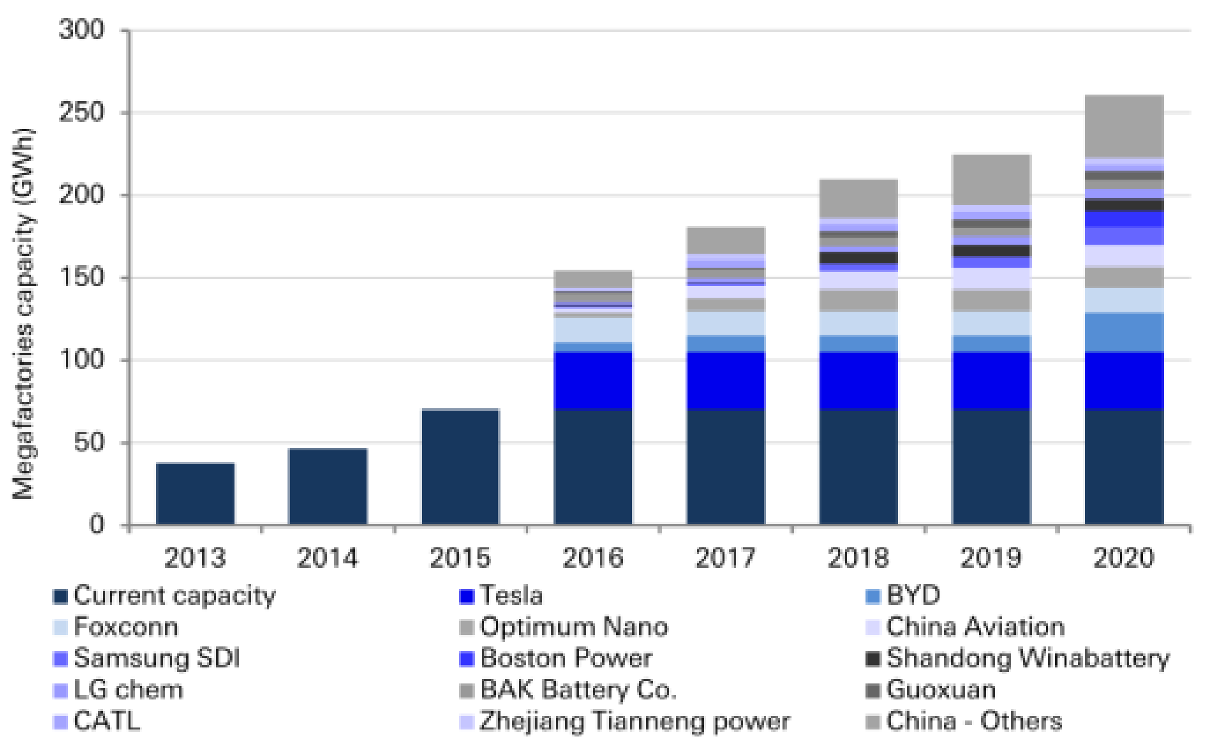


Figure 6: Flow of LIB cells between major trading partners (dark shades represent exports, lighter shades represent imports) [21].

The chart in Fig. 7 [6] shows the evolution of the LIB production capacity considering available, ongoing and announced capacities targeting xEV and ES applications: production capacity is expected to rise from ca. 70 GWh in 2015 over 150 GWh in 2016 to 260 GWh by 2020. Similar numbers, more than doubling in 5 year, from 103 MWh in 2016 to 278 MWh in 2021 are mentioned in [16], as well as in [12]: from 80 GWh in 2016 to 285 GWh in 2020.

[i] More recent information on trade flows than dating from 2014 could not be found.



Source: Deutsche Bank, company data

Figure 7: LIB cell production capacity for xEV and ES worldwide (from [6], based on info from a number of sources].

Figure 7 shows that, with the exception of the Tesla-Panasonic factory (35 GWh), only companies in Asia contribute to the expanding global LIB manufacturing capacity for xEVs and ES. In China alone up to 9 factories are being constructed which will raise production capacity from 16 GWh at present to a total of 107 GWh in 2020 [22] and 120 GWh in 2021 [23], thereby bringing China's share in global LIB production to 65%. Some of these new plants are expected to be huge, with the CATL facility at 50 GWh being by far the largest. However, not exclusively Chinese companies are involved in manufacturing capacity increases in China; also Korean, Japanese and US companies contribute[j].

Whereas Fig. 7 shows the expected global nominal capacity increases for LIBs for xEV and ES till 2020, Fig. 8 includes projections till 2025 on "realistic" capacity increases, considering the maximum yield of present-day factories and the degree of actual capacity utilisation [7]. Fig. 8 also includes an optimistic and a conservative xEV+ES demand projection[k]. For both the optimistic and conservative scenario, the projected demand is expected to exceed the estimated realistic capacity in 2022-2023.

While East-Asian companies dominate cell production and until recently contributed practically exclusively to the ongoing and planned capacity expansions, a number of plans for giga-factories in other parts of the world have been announced over the last months [24], [25]: Thailand (50 GWh by 2020), US (15 GWh in New York State, 4 GWh in Los Angeles), Australia (2 locations, resp. 1 and 15 GWh), India (unspecified location and capacity, [26]), EU (see Table 2 below), evidencing the tendency for cell production to increasingly locate closer to areas of expected demand growth. Also Asian companies are establishing factories for cell components in other parts of the world, such as e.g. a separator factory in Europe [27].

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j Conflicting information exists on capacity increases in China by non-Chinese companies.
k In line with the data in Table 1, i.e. not considering the earlier mass uptake of xEVs forecasted in [12], [13].

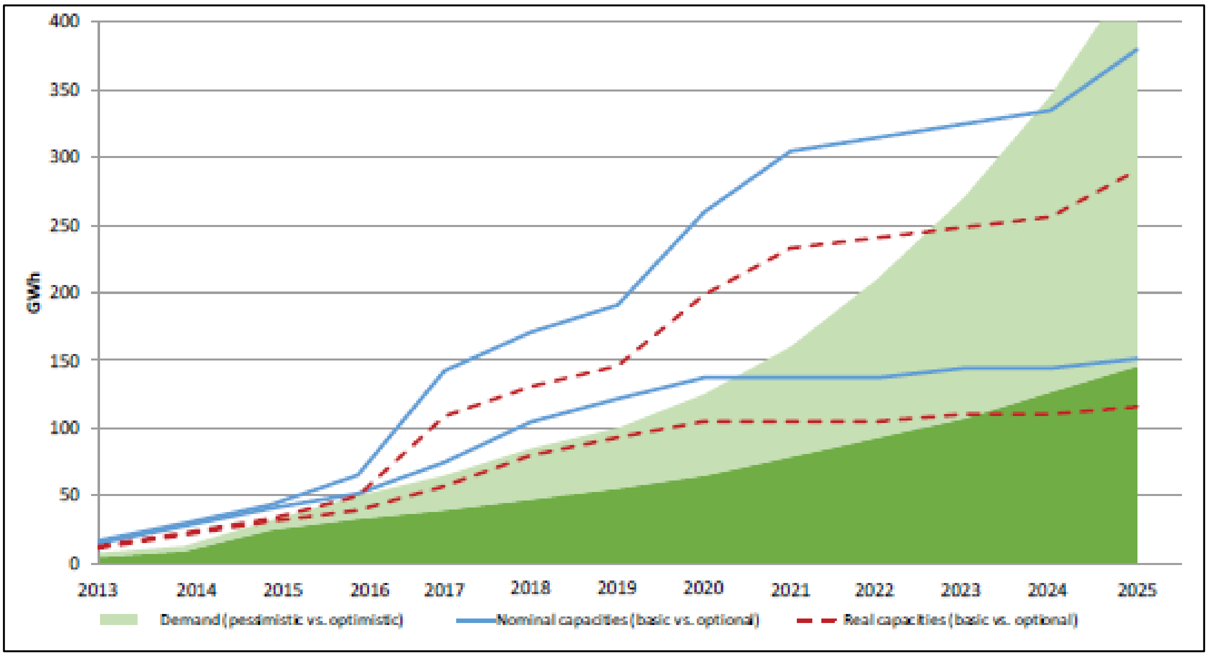

Figure 8: Global LIB cell production capacity for xEV and ES (lines) and projected demand evolution (shaded areas) [7].

The current lack of a domestic LIB cell manufacturing base in the EU jeopardises the competitive position of EU industrial customers of LIBs for xEV and ES applications because of security of supply chain issues, increased costs due to transportation, loss of part of the value, time delays, relinquished control on quality and limitations on design options. Whereas establishment of a domestic LIB cell manufacturing chain by European manufacturers is the obviously preferred option to address this competitive disadvantage, Korean cell producers have already seized the opportunity and are currently establishing cell manufacturing capacity in Europe in which, to strengthen their position, they go for vertical integration from component to pack production [19][l]. The opposite also applies to some extent: European battery pack assemblers investing in facilities in China and extending into local battery cell manufacturing through a local joint venture, as demonstrated by the recent investment made by a major European car manufacturer[m] [28].

Table 2 lists known initiatives and plans for establishing battery cell/pack manufacturing in Europe for xEV and ES applications. The only currently operational facilities by EU companies in the EU are a number of relatively small manufacturing and assembly plants.

[l] Whereas not embarking on production in Europe yet, CATL (China) is establishing R&D facilities in Germany, and has started collaboration with European automotive manufacturers PSA and BMW.

[m] Daimler through BBAC, its joint venture with BAIC. Such investments offer the advantage of allowing foreign manufacturers to avoid the 25% import tariff that applies to imported vehicles being sold in China.

Who	Where	Annual Capacity	When	Comments	references
CELLS					
LG Chem (KR)	Wroclaw, PL	100.000 EV batteries, > 2 GWh	2018		29,30,31,32
Samsung SDI (KR)	Göd, HU	50.000 EV batteries, 2.5 GWh	2018H2		33,34
SK Innovation (KR)	HU or CZ	?	2018H2		35
Tesla (US) with Panasonic (JP)	DE, others?[n]	?			36,37
Northvolt (SE)	?, SE	8 GWh initially, 32 GWh final	2020 - 2024	• Target cost 80-110$/kWh; • Use of well-known, foundry-based manufacturing process; • vertical integration; new chemistries >2025; • aims at being replicable	38,39
TerraE (DE)	DE (2 locations)	6-8 GWh; 34 GWh (2028)	2028 final	• consortium consisting of companies throughout the supply chain including infrastructure, manufacturing planners, material producers, machine engineering groups, cell manufacturers and industrial consumers • EV + ES • Operated according to the "foundry principle" • Development of cells based on results from Giga-LIB project (DE)	40,41,42,43
SERI (IT)	IT	200 MWh	2018	• Preparing vertical supply chain in IT • EV+ES	44
Monbat (BG)	Nordhausen, DE	?	?	• Merger of two existing companies into new entity EAS Batteries • First LFP, later other chemistries	45
PACKS					
Nissan (JP)	Sunderland, UK	60.000 packs, 1.5 GWh	2013	cells from AESC (joint venture between Nissan and NEC, JP), taken over by GSR (China)	46
BMZ (Deutsche Accumotive)[o]	Kamenz, DE	80 million packs totalling 5 GWh	2018-2020	cells from LGChem	47,48
Kreisel Electric GmbH	Rainbach, AT	800 MWh		cells from Samsung	2
Continental	Nuremberg, DE	330 MWh	2008		2
Dow Kokam (KR)	FR	105 MWh			2
Bolloré	FR	300 MWh			2
BYD (CN)	HU	400 buses	2018		49

Table 2: Initiatives and plans for LIB cell and pack producing facilities in the EU

n Locations in EU candidate for establishing a Tesla gigafactory are: Trollhattan (SE), Vaasa (FI), Tilburg (NL), Kamenz (DE), Fessenheim (FR), Paterna (ES), Guarda (PT)
o Daimler Deutsche Accumotive (Daimler battery subsidiary) will triple its pack production capacity by building a second plant. Daimler shut down its cell manufacturing subsidiary Li-Tec in 2015.

Fig. 9 compares the expected market volume of xEVs in the EU (see chapter 3) with the expected evolution of cell manufacturing capacity in Europe from Table 2 and demonstrates that currently known planned cell production capacities in Europe are likely to be sufficient to meet the minimum projected European demand for xEVs in 2025, but would definitely not suffice for meeting the maximum demand estimate. The figure also reveals that 2030 targets included in the DoI are likely to be met.

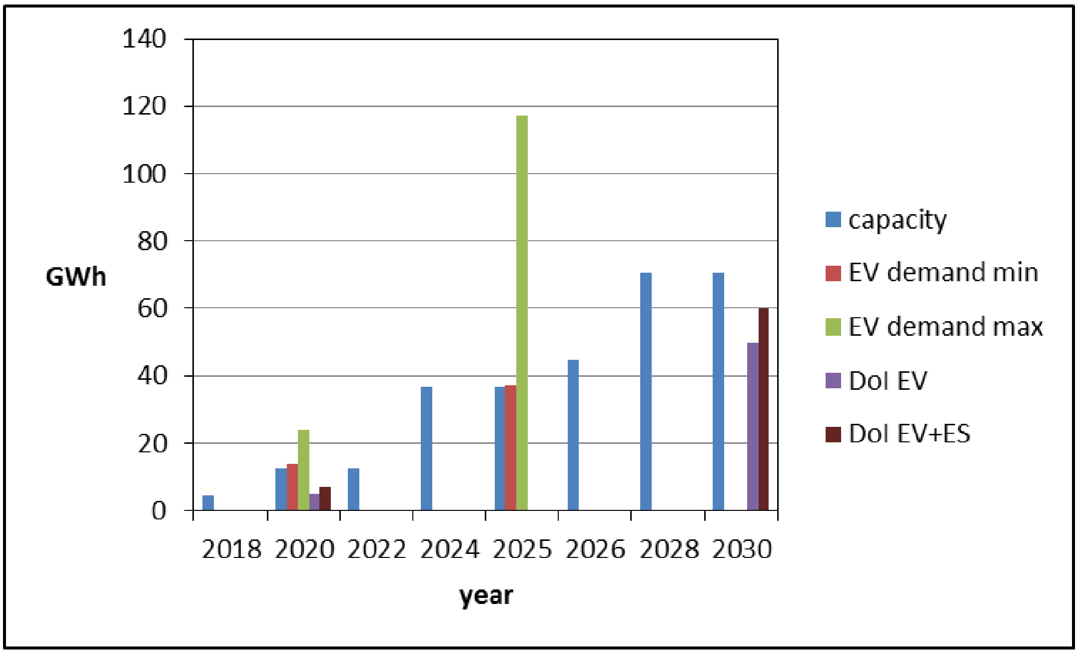

Figure 9: Comparison of planned production capacity in Europe, European xEV demand and manufacturing volume targets from the DoI [3].

It is worth mentioning here that in the aftermath of "dieselgate", VW has announced stepping up its production of EVs. Whereas VW currently relies on external battery suppliers, management has made a pledge to create 9000 new jobs in the area of battery production and mobility services at factories in Germany as part of efforts to shift toward electric and self-driving cars [50]. In 2016 VW reckoned it will require about 150 GWh of battery production capacity per year (date unspecified) and indicated it considers using solid-state batteries[p], which would require an investment of 10 B€[q]. Recently also Toyota has indicated intention to use solid-state batteries for its future EVs as of 2022 [51].

Most recently VW predicts that, should all OEMs target 25 percent of sales volumes from battery electric vehicles by 2025, there will be a massive shortage of LIB cells as demand raises to some 1.5 TWh [r] (equivalent to 40 Tesla gigafactories, each with an annual capacity to produce 35 GWh of lithium ion cells) [52]. To reduce this manufacturing volume need, VW is currently investigating powering its future EVs with higher energy density lithium-sulphur cells.

[p] Solid state batteries (generation-4 LIBs, see chapter 5) offer higher energy density (higher range), enhanced intrinsic safety and reduced charge time compared to lower-generation LIBs, but still suffer from lower cyclic performance.

[q] In this context, it is worth noting that Bosch has bought US solid-state battery maker Seeo in 2014, a move that could make it a potential candidate for localized cell making in Europe.

[r] The associated capacity need even exceeds the highest estimate of demand for xEV in [12] and [13] of 1.33 TWh.

Take-Aways #3-5

- Current LIB manufacturing capacity is concentrated in Asia and is not able to meet the increasing global demand for xEV and ES. LIB cell manufacturers, in particular Asian ones, are investing in additional and new production capabilities close to the major demand centres, i.e. in Asia, US and Europe.
- The absence of domestic LIB cell manufacturing in the EU negatively affects the competitiveness of European xEV producers and ES service providers.
- Currently known planned cell production capacities in Europe are expected to suffice for meeting the minimum estimate of xEV deployment in Europe in 2025, but most likely will not be able to meet the maximum projected demand.

5 Opportunities for EU competitiveness in LIB cell manufacturing

Fig. 10 depicts the battery value chain [2] and highlights that it contains a transition from cost-dominated to value-dominated segments. In the latter, such as battery pack manufacturing, the decisive criterion for a positive business case is the ability to meet the specific requirements of the customer (both OEMs of xEVs and ES operators). Hence, competition at global level does not play an important part for LIB pack manufacturing. The following discussion therefore does not consider EU competitiveness in LIB pack manufacturing.

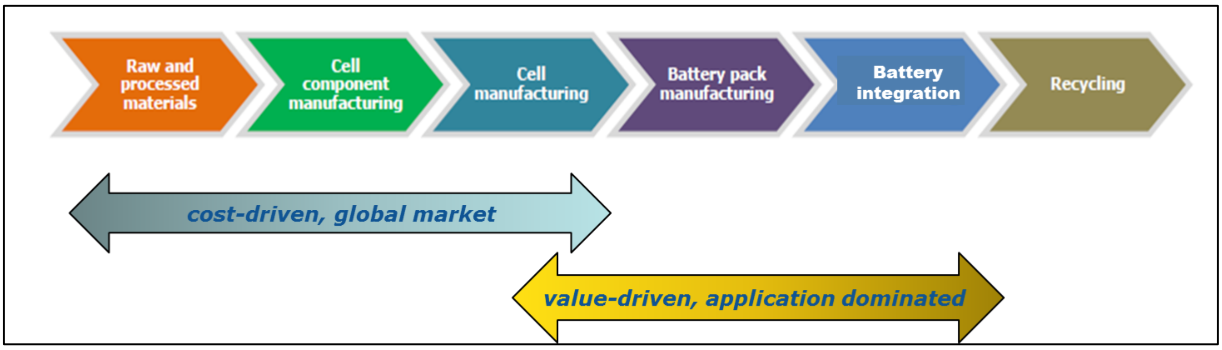

Figure 10: LIB value chain (based on [2]).

On the other hand, segments in the chain upstream from pack manufacturing, covering materials processing, manufacturing of components and of cells[s], are primarily cost-dominated and therefore subject to worldwide competition. Considerations on EU competitiveness should hence in first instance cover these segments and target technology innovation in cell chemistries, in cell formats and in cell manufacturing technologies/processes.

This view is confirmed by the results of a survey carried out among European battery experts on the position of the EU in the global battery value chain compared to that of the rest of the world in the frame of the Batstorm project [20]. As indicated in Fig. 11, EU-based companies are perceived strong only in the downstream stages of the battery value chain and overall weaker in the materials and cell manufacturing segments. Measures to enhance EU competitiveness should therefore in first instance target these segments.

It is to be noted here that global competitiveness of EU industry in the LIB sector – and the associated benefits for growth and jobs – critically depend on the ability for EU industry to also serve non-EU markets with battery cells and packs, as well as with final products (xEV and ES products). This applies specifically for being able to supply the boosting xEV market in China. Therefore trade barriers which hamper market access of foreign-produced final products should be removed, as well as requirements on a minimum share of domestic production of LIBs that needs to be incorporated in these end products[t].

[s] In general, LIB cells are to some extent customised to the end-use application and their manufacture is therefore also partly value-driven.

[t] In the 2016 list of companies allowed to supply batteries in China, not a single foreign company is included. Draft guidelines issued at the end of 2016 moreover specify that battery manufacturers need a minimum of 8 GWh annual production capacity in China in order for car owners to qualify for EV purchase subsidies; only 2 Chinese producers (BYD and CATL) can meet this requirement.

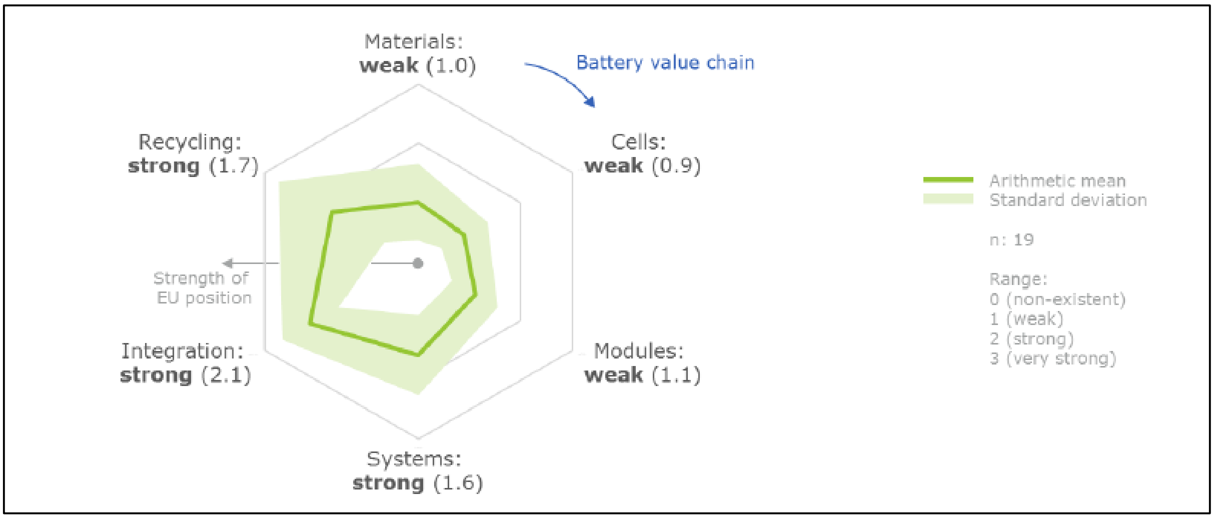

Figure 11: Rating of EU position in the global LIB value chain [20].

At present, optimised LIB cells of generation-1 and -2a (Fig. 12, [19]) represent the core technology for xEVs and for ES. Given the lead time from R&D on battery materials to their actual incorporation in large scale production of cells, these generations – and incremental improvements to them – are expected to remain the chemistry of choice for at least the next 10 years. Because manufacturing capacity build-up for these chemistries is already ongoing in Asia – particularly in China – it does not seem effective to spend significant efforts to establish a mass production chain in Europe on cell chemistries up to and including generation-2a [u]. Efforts for establishing manufacturing capacity in Europe should hence primarily target LIB cells of generation-2b and beyond and should moreover focus on the operations in the production chain which are critical to quality of the end-product, as they represent areas where IP may confer competitive advantage[v]. Furthermore, advantages gained in these production processes may be transferable to other end-applications and thereby offer increased market potential.

Cell generation	Cell chemistry	
Generation 5	• Li/O_2 (lithium-air)	> 2025 ?
Generation 4	• All-solid-state with lithium anode • Conversion materials (primarily lithium-sulphur)	
Generation 3b	• Cathode: HE-NCM, HVS (high-voltage spinel) • Anode: silicon/carbon	~ 2025
Generation 3a	• Cathode: NCM622 to NCM811 • Anode: carbon (graphite) + silicon component (5-10%)	~ 2020
Generation 2b	• Cathode: NCM523 to NCM622 • Anode: carbon	current
Generation 2a	• Cathode: NCM111 • Anode: 100% carbon	current
Generation 1	• Cathode: LFP, NCA • Anode: 100% carbon	current

Figure 12: Classification of LIB cell chemistries [19].

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u This obviously does not rule out continuation and/or uptake of EU industrial involvement in the production of components for generation-1 and-2a LIBs, which is also a production chain segment subject to global competition (see e.g. Umicore new capacity in China and South Korea at existing sites for production of NMC cathodes for automotive applications).

v This applies primarily for cathode manufacturing and explains why many of the Asian cell manufacturers also produce their cathodes themselves.

When assessing the attractiveness and feasibility of establishing LIB cell manufacturing capacities in Europe the following aspects should be considered:

(1) access to supply (in terms of import dependence of raw materials[w]),

(2) cost competitiveness,

(3) added value beyond cost which may differentiate EU companies from Asian incumbents, and

(4) sustained R&I efforts.

These factors are discussed below.

5.1 Supply of materials

Critical materials for LIB (i.e. those having high supply dependence and economic importance) are cobalt, natural graphite and silicon metal [2]. China dominates global production of natural graphite and of silicon metal and steadily increases its control of cobalt production[x] . Moreover, whereas lithium itself is not considered a critical material, China is home to the majority of the world's lithium refining facilities. As a result, China has acquired and is still expanding its dominant position in the LIB supply chain and there is little possibility for EU industry to become competitive in raw material supply for LIB.

However, building up and strengthening EU activity in material supply may have a pay-off in terms of reduced future dependence on imported battery component materials (particularly Co and Li, and high-purity Ni later on) for cell manufacturing and of shortening supply distances and times. This can be achieved through:

- developing domestic sourcing of Li (Sweden, Finland, Portugal, Czech Republic, Serbia), Co (Finland), graphite (Sweden) – this approach is being investigated for the establishment of a battery megafactory in Scandinavia [53] and of a production facility for cathode materials in Europe [54].
- substitution of Co by other materials (already ongoing for optimised cathodes) and mitigating the dependence on their supply (e.g. by expanding EU domestic production of high-grade Ni).
- increasing the volumes of recycling/reuse of battery materials.

However, raw materials (and cell components) sourced from the EU will not be able to meet the demand. Hence, security in their supply is a precondition for setting up LIB cell manufacturing capabilities in the EU.

5.2 Enhanced cost competitiveness

Identifying measures to reduce costs requires analysis of the cost structure. Major cost components for LIB cells are material (supply and logistics), labour, energy, depreciation, R&D and SGA (selling, general and administrative expenses). Battery cells typically account for 70% of the total value of the battery pack (see Fig. 1), and cell costs are roughly composed of 50% materials and 50% manufacturing.

5.2.1 Materials related costs:

Because all cell manufacturers, including foreign incumbents, have to import raw materials, there is no direct competitive disadvantage for the EU from the raw material supply side. Non-EU manufacturers may however benefit from lower transportation distances, times and costs for acquiring the high-purity materials needed for cell manufacture. In this respect, Asian LIB manufacturers, and Chinese ones in particular,

[w] From a non-technological point of view also the availability of and access to competences, labour and capital is important.

[x] In particular by increasing its control of Co-production in the Democratic Republic of Congo which produces more than half the global supply and of which the price has doubled over the last year.

have a competitive advantage because of the concentration of Li-refining capacity in China. In future, exploitation of indigenous EU resources of Li from geothermal brines may partially relax this situation[y] [55].

Cost for materials can be reduced through the development and large-scale production of better performing materials for cathodes, anodes, separators and electrolytes. In this area, Europe can profit from its high quality R&D[z], covering both material design and development, as well as manufacturing processes and technologies.

Additionally, increased recycling of materials from end-of-life batteries in the EU will result in reduced need of primary raw materials and lower material transport costs. Accordingly, the DoI [3] targets 70% battery collection/takeback by 2020 and 85% by 2030, and 50% recycling efficiency by 2020. Also increased use of LIBs after they have reached their end-of-life in a first-use application contributes to reduced material needs and costs.

5.2.2 Cell manufacturing costs:

Costs for cell manufacturing are typically composed of energy (10%), labour (10%), maintenance (20%) and depreciation (60%)[aa] [56]. Because labour constitutes a minor part of manufacturing costs, the difference in wages in Asia, China, US and EU does not have a large impact. On the other hand, established (i.e. Asian) cell producers have a cost advantage resulting from production scale and expertise, supply chain optimisation, vertical integration and partnerships that have been developed over the last decades in LIB manufacturing for consumer electronic applications.

As shown in Fig. 3, cell manufacturing costs critically depend on the manufacturing volume. A 2015 model-based analysis [7] of the overall manufacturing costs for LIB cells (generations 2a, 2b and 3a) for BEVs[bb] as a function of the manufacturing volume has revealed that for a maximum allowable manufacturing cost of 130 €/kWh in 2020, the manufacturing of 2nd generation LIB cells is not economical in Germany for volumes ranging between 1 GWh/y and 13 GWh/y. The threshold production volume for LIB of generation-3a to become economical lies at 9 GWh/y. The model reveals that under these conditions, mass manufacturing in Germany can be competitive with that in Korea and in China (Japan was not included in the analysis). Other sources [57] indicate a 2019 threshold production capacity of 4.5 GWh/y, for a 100 €/kWh threshold manufacturing cost.

5.3 Offering added value beyond cost

Competing with foreign global economies (especially in Asia) in the battery sector on a cost-only basis is difficult, considering the supply and market advantages enjoyed by Asian players. To overcome this and gain competitive ground, Europe needs to differentiate itself on other factors including (environmental) sustainability and safety, as well as performance.

The EU competitive position can benefit from more efficient use of resources resulting in a reduction of the energy, CO_2 and material footprints in the overall manufacturing chain. As illustrated in Fig. 13, the largest contributions to energy use and therefore to CO_2 emissions along those segments in the production chain in Fig. 10 which are subject to worldwide competition, originate from electrode production (cathode and anode) [58].

Typically, the energy required to manufacture a LIB is about 500 times its energy storage capacity. This can be lowered by increasing process efficiency, through e.g.

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[y] As product of long-term water-rock interactions at elevated temperatures at depth, brines contain dissolved chemical components at various concentrations. Despite the low concentrations, they contain significant quantities of select minerals that could be recovered due to the large volumes of brine used by geothermal power plants. A project coordinated by ERAMET is currently ongoing under the EIP on Raw Materials.

[z] Note however that Europe lags behind in number of patents for Li-ion batteries and applications: only Bosch (DE) and CEA (FR) figure among the top-30 global entities holding Li-ion patents [20].

[aa] These numbers vary with cell chemistry and format.

[bb] For cell types and formats used in PHEVs, higher costs prevail (see Fig. 3).

reducing the size of dry rooms, through optimizing process steps (e.g. reduction/elimination of formation[cc]) and by better overall integration allowing re-use of energy. EU has a well-developed equipment manufacturing industry which should be able to capitalise on this to secure its place in the attractive growth market of LIB cell manufacturing plants[dd].

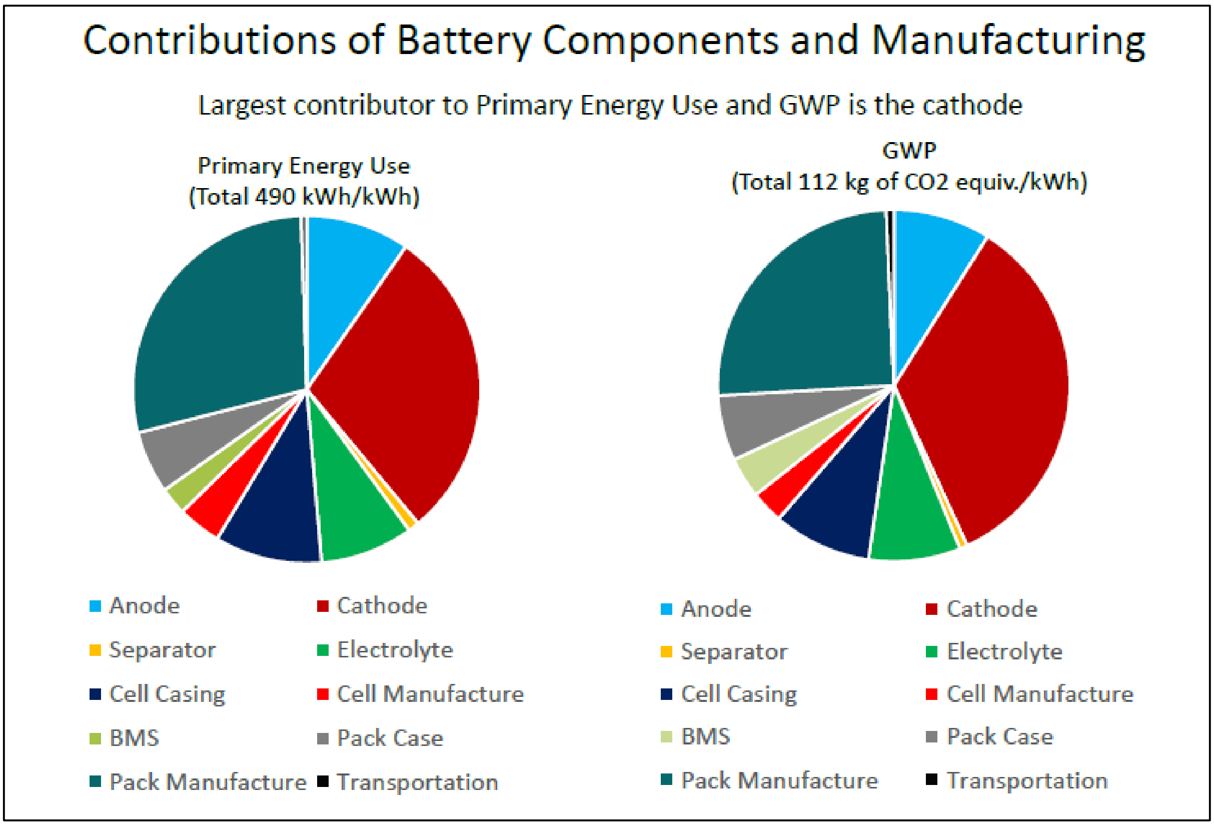

Figure 13: Primary energy consumption and CO_2 emissions for LIB manufacturing [58]. (GWP = Global Warming Potential)

The high energy intensity of electrode production underscores the importance of availability of cheap energy for competitiveness[ee]. From the point of view of reducing CO_2 footprint, switching to renewable energy for cell manufacturing is an obvious approach[ff]. Furthermore, locating battery cell production in Europe avoids the CO_2 emissions linked to the transportation to the EU of cells manufactured in Asia, with added benefits in terms of reduction of associated time and cost.

Reduction of waste can be achieved by process-measures (such as e.g. replacing organic solvents in electrode fabrication and use of biodegradable materials) and by enhanced use of and improving the efficiency of recycling processes. EU industry has a well-proven track record in the latter and should exploit and strengthen its dominant position[gg]. In particular, it can profit from implementing cost-effective recycling approaches able to deal with the several different LIB chemistries used in different types of xEVs according to their specific needs for energy, power, safety, lifespan and cost.

[cc] A controlled charge and discharge cycle designed to activate the battery materials.

[dd] Some EU equipment suppliers (Manz, PEC) already serve Asian cell producers and could exploit their know-how for the benefit of establishing state of the art LIB cell manufacturing plants in the EU.

[ee] Access to cheap energy is even more relevant when considering possible upstream integration with refinery operations which are also very energy-intensive.

[ff] This approach is applied in the Tesla gigafactory and is also claimed a major consideration for locating the Northvolt manufacturing facility in Scandinavia.

[gg] The ongoing revision of the Battery Directive 2006/66/EC is critical in this respect.

Further added value can come from enabling second use of lithium-ion automotive batteries after first use. When xEV LIBs no longer meet the requirements for continued use in a vehicle, they still retain sufficient energy storage capacity which can be potentially re-purposed and deployed for stationary storage applications [59] and thereby results in a reduction of the lifetime cost of ownership of the battery[hh]. However, full exploitation of the 2nd-life potential[ii] requires additional efforts for assessing and quantifying the technical feasibility as well as the environmental, economic and social impacts of xEV battery second use. The former requires a structured methodology for State of Health (SoH) assessment [60], whereas the latter needs systematic analysis through Life Cycle Assessment.

The competitive position of EU industry in setting up and operating new state-of-the-art LIB cell manufacturing capacities can also benefit from being able to ensure higher operational safety along the LIB cell production chain than that achieved in existing plants and avoid accidents such as those that have occurred in a number of cell or battery pack production facilities worldwide[jj] [61], [62]. Also numerous accidents have occurred at battery recycling facilities [61]. Although the exact cause for many accidents remains unknown, some of them have been linked to human errors in either the product and process design, or in testing product quality and safety. Possible measures to improve safety in the production chain include selection of more intrinsically safe materials [63] (e.g. less flammable and less toxic electrolytes), increased process automation, use of better fit-for-purpose testing methodologies, improved battery and cell labelling to facilitate the sorting process [64], etc.

Manufacturing process-related innovation measures to seize the competitiveness opportunities described above are discussed in Annex II.

In addition to the factors identified above which directly affect LIB cell manufacturing, opportunities also exist for European industry actors to establish and/or strengthen their global competitive position in the overall e-mobility and stationary storage markets. This applies in first instance for EU battery plant manufacturers, but also for other actors in the overall LIB value chain. Whereas upstream from cell manufacturing some EU industries are already active in the production of LIB electrode materials and/or want to establish an activity in this area in Europe [54]; downstream these include producers of battery management systems, of power electronics suppliers, system integrators, grid integrators (V2G) and battery recyclers.

Further opportunities arise for stationary storage applications because batteries in general and LIB in particular cannot meet the demand for high energy storage capacity combined with high power capacity over the range of response/discharge times required in a number of applications [65]. Such applications necessitate the development of hybrid energy storage systems to deliver power capacity, energy duration and cycle life in a single system. In particular the increased complexity in hardware (inverters, converters, …) and software for hybrid energy storage systems offers economic opportunities [66].

Finally, it should be noted that EU competitiveness in the LIB sector will also benefit from deployment of LIBs in numerous other applications besides xEVs (incl. vans and buses) and ES, such as 2- and 3-wheelers, material handling vehicles (forklifts, tow trucks), ferries, medical devices, garden equipment, cordless power tools, etc., which also constitute a growing market relying on the availability of safe and high-performant LIBs.

[hh] Currently Renault-Nissan, BMW, VW and BYD have linked up with utilities for exploiting used xEV batteries for stationary storage purposes.

[ii] Estimated globally at 3.6 GWh in 2025 to 12 GWh in 2030 [59], resp. at 26 GWh by 2025 [13], non-negligible compared to the market for 1st life ES applications in Table 1.

[jj] explosion at Matsushita Battery Industry factory in Japan in August 1997, large fire at the BMZ battery pack manufacturing facility in Germany in August 2008, fire in February 2017 at the waste depository of Samsung SDI facility in China.

5.4 Need for sustained R&I efforts

To be able to exploit the above indicated measures to establish a competitive position in LIB cell manufacturing, there is a need for sustained and even stepped-up R&I efforts. Recent Commission Communications and Staff Working Documents have outlined the priorities for batteries, including LIB [67], [68]. Additionally, the Implementation Plan of Action 7 of the Integrated SET-Plan, to be delivered by Nov. 2017, will outline the activities, actors and means by European industry, Member States and the Commission to realise the set of targets contained in the DoI [3].

Take Aways # 6-9

- Considerations on EU competitiveness in LIB cell manufacturing should target innovation in cell chemistries, formats and manufacturing technologies/processes.
- Efforts for establishing LIB cell manufacturing capacity in the EU should primarily target LIB cells of generation-2b and beyond and should focus on production stages which are critical for LIB quality, performance and safety.
- Competing with non-EU LIB cell producers on cost-only basis is unlikely to be successful. A competitive EU LIB cell production should offer added value beyond cost, in terms of enhanced sustainability, safety and performance.
- Sustained and even increased R&I efforts, covering materials and manufacturing processes in terms of technical, safety and sustainability performance are needed to underpin competitive battery manufacturing in the EU.

6 Investment costs for setting up LIB production capacity

Learning curves (see Annex I) can be exploited to estimate the cumulative financial effort required for establishing a given production volume of technology products, e.g. LIB cells or packs. As shown in Fig. I.2 of Annex I, using a single historical data set of EV battery manufacturing prices (used as proxy of cost) as a function of the cumulative installed capacity, the overall budget required for deploying 300 GWh of EV batteries globally by 2025 (as per Table 1), is estimated at 39 B$. Assuming no change in learning rate, the larger predicted global demand in [12], [13] of 1.3 TWh by 2025 would require around 80 B$.

Table 3 lists investment costs published for a number of planned/announced LIB cell mega-factories (unless otherwise indicated, references as in Table 2) as well as from a recent German study [19]:

LIB cell production plant	Capacity (GWh/y)	reported investment cost	Specific investment cost
NPE [19]	13	1.3 B€	100 €/kWh
NPE [19]	4.5	700 M€	155 €/kWh
Tesla (Nevada)	35	5 B$	142 $/kWh
Panasonic (China) [69]	2.5	0.5 B$	200 $/kWh
LG Chem (PL)	2	340 M$	170 $/kWh
Samsung SDI (HU)	2.5	300 M€	120 €/kWh
Northvolt (SE)	32	4 B€	125 €/kWh
TerraE (DE)	8	1 B€	125 €/kWh
Energy Absolute (Thailand) [70]	1	88 M$	88 $/kWh
Dynavolt (CN) [71]	6	400 M€	67 €/kWh
VW (DE)[kk] [50]	150	10 B€	66 €/kWh

Table 3: Investment costs of planned LIB cell manufacturing plants.

The investment costs estimated for new to-be-built LIB cell manufacturing plants from Table 3 are shown as a function of their production capacity in Figure 14. The figure also includes the estimated required financial effort as a function of additional manufacturing volume derived from the learning curve considered in Annex I, as well as the specific investment costs quoted in [5] for the periods 2011-2014 and 2014-2016. The slight overprediction of investment costs by the solid curve can be explained by the pack to cell cost ratio (see e.g. Figs. 1, 2). Based on the good agreement between all data, the investment cost corresponding to the expected needed manufacturing capacity increase in Europe can be determined from the curve shown in Fig. 14.

[kk] Solid state batteries

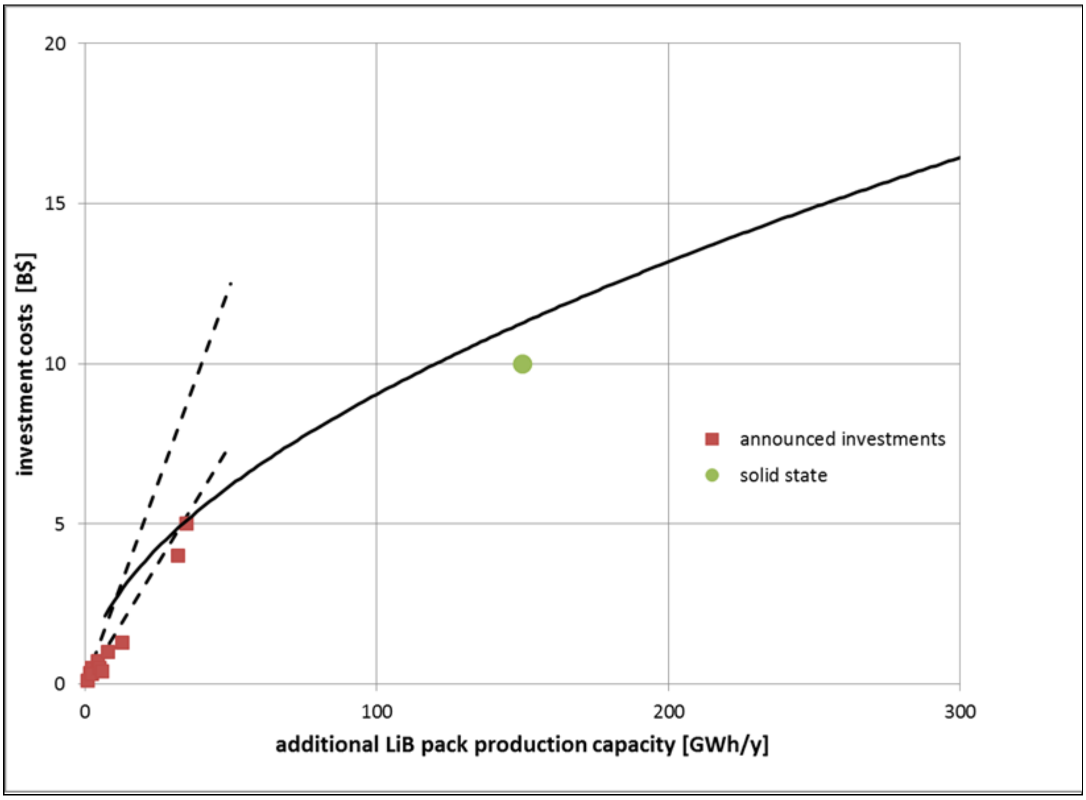

Figure 14: Investment cost as a function of additional pack production capacity. The solid curve is taken from Annex I, whereas symbols refer to the announced investments listed in Table 3 (the data point corresponding to solid-state LIB (green symbol) has not been considered in the regression). Dashed lines represent specific investment costs mentioned in [5].

Take Aways # 10-11

- Learning curves – although subject to a number of intrinsic and data availability limitations - enable the projection of future technology costs, from which the cumulative investment needed for deploying the technology (in this case LIBs) can be estimated. The latter can subsequently be used to assess the investment costs for setting up new, additional manufacturing capacity.
- Specific investment costs for new LIB cell manufacturing capacity has decreased to around $ 150/kWh and will further decrease as additional manufacturing capacities come on line.

7 Job creation potential

Establishing a domestic LIB cell production industry is expected to have a major effect on employment in the EU. The aforementioned German study [19] estimates creation of 1050 to 1300 new direct jobs for a 13 GWh/y capacity plant requiring an investment of 1.3 B€: 750-900 employees working in 4 shifts, 150-200 in administration, procurement and sales and another 150-200 in R&D. More than 3000 indirect jobs could be created within the immediate vicinity of the cell producing plant for suppliers, subcontractors, logistics, mechanical engineering, construction and automatization companies. Published data on job creation from other sources are included in Table 4 (unless otherwise indicated, references as in Table 2).

LIB cell production plant	Capacity (GWh/y)	expected job creation
NPE [19]	13	1300 direct, 3000 indirect
Tesla (Nevada)	35	6500
Panasonic (China) [72]	2.5	500
Northvolt (SE)	32	2500-3000 direct, 20000+ indirect
TerraE (DE)	8	400 direct
Boston Energy and Innovation (Australia) [73]	15	1000 in manufacturing, 1000 direct support, 5000 indirect
VW (DE)[ll] [52]	150	9000

Table 4: Job creation potential of planned LIB cell manufacturing plants.

Fig. 15 shows the number of direct jobs created as a function of the annual production capacity based on the data in Table 4. For the range of cell manufacturing capacity covered, between 90 to 180 direct jobs are expected to be created per GWh of LIB cells produced annually (excluding solid-state).

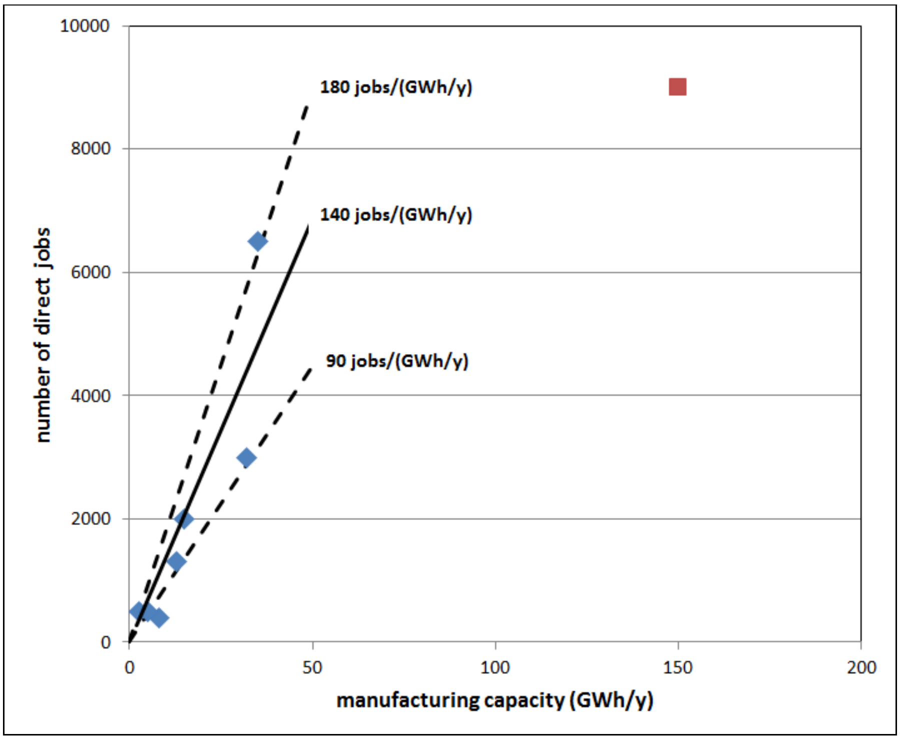

Figure 15: Estimated number of direct jobs created [data from Table 4, data point corresponding to solid-state LIB (red symbol) not considered in the regression].

[ll] Solid state batteries

Whereas the job creation numbers listed in the above table and figure refer to cell manufacturing, the establishment of new LIB cell production capacities in Europe in response to the globally booming market of xEVs and ES is expected to strengthen all European industries active along entire the battery value chain. In this context, the US Supercharge initiative, a public-private partnership proposed in 2016 for co-funding by the Department of Commerce and aimed at achieving US global leadership in advanced battery manufacturing, has an objective of supporting 180 GWh of domestic LIB manufacturing capacity with an estimated 120.000 job creation potential [74]. Comparing the latter number with the data in Fig. 15 reveals a multiplication factor between the total number of jobs created along the complete value chain and the direct ones created in cell manufacturing in the range of 3.7 to 7.5, which agrees with the ratio of indirect to direct jobs created from the available data in Table 4.

Take Away #12

> Establishing a competitive LIB cell manufacturing capability in the EU is expected to create between 90 and 180 direct jobs per GWh/y production volume.

8 Requirements for competitive domestic EU LIB cell manufacturing

Establishing competitive LIB cell manufacturing in Europe by European companies is feasible but depends on two main factors: reducing risk for private investors (see investment costs in Table 3 and Annex I) and realising economies of scale. To achieve this, a set of conditions have to be met:

- Industrial cell production is primarily targeted at "advanced" LIB chemistries, i.e. generation-2b and beyond
- A secure material supply is guaranteed, as well as access to non-EU markets
- Flexibility in the design of the facility allows for manufacturing of different chemistries and sizes/formats
- The facility has a sufficiently large capacity, say > 5 GWh/y, to enable exploitation of technology learning
- The plant can be operated for a long enough period at a sufficiently high capacity utilisation rate to enable generating profit following the period of negative cash-flow upon production start
- A skilled competent workforce is available

If the above "sine qua non" requirements can be met, the following factors contribute positively to a business case by strengthening the position of European newcomers vis-à-vis Asian manufacturers who "copy and paste" from their proven manufacturing lines:

- Geographical proximity of customers, in first instance of OEMs of xEVs (reduction of transport costs, facilitation of exchange of technical specifications, fast response and delivery times)
- Establishment and exploitation of synergies and knowledge spill-overs through co-location, vertical integration or joint ventures along the production chain, at least up to and including cell manufacturing (borrow from the Airbus model?)
- Reduced energy and CO_2 footprint
- Optimum re-use of end-of-first-life xEV batteries or of materials recycled from them
- Diversification to non-xEV markets, in particular ES and high-value niches such as power tools
- Adequate provisions for IP protection
- Reduced time for siting and permitting processes

While fully realising that decisions on mass production of LIB cells in the EU are in the hands of EU industry, the Commission can undertake the following actions to reduce the investment risk, so that EU industry can reap the benefits of a large and fast-growing global LIB cell and cell manufacturing market. Successful implementation of these actions requires commitment and active involvement of all stakeholders along the LIB value chain. The activities by Commission services along the value chain are shown in Annex III, taken from the input prepared in the formulation of the Mobility Package [75].

a) Overall Energy Union policy-level

- Maintain and strengthen the commitment to the transition of the overall EU energy system, as outlined in the five overarching objectives of the Energy Union. In particular pursue the legislative initiatives already started with RED II, the new electricity market design, the revision of the CO_2 emissions of LDV legislation, to foster deeper and accelerated integration and coupling of the power, transport and heat sectors through deployment of energy storage solutions, a.o. through the use of LIBs (DG ENER, CLIMA, MOVE).

- As indicated in the ACEI Communication [67], make increasing use of the possibility under the Annual Union Work Programme for Standardisation of including requests to the European Standards Organisations (ESOs) to develop European standards to support implementation of Energy Union objectives, notably for the decarbonisation of the economy and support for green public procurement (DG ENER, JRC, GROW).
- As outlined in the ACEI Communication [67], optimally exploit the potential of current EU-level financial instruments, enhance the synergies between them and where necessary deploy new, targeted financial instruments to lower the risk of investments in untested but promising clean energy technologies or business models and thereby contribute to more favourable market access conditions (DG ENER, CLIMA, ECFIN, GROW, REGIO, MOVE, COMP, …).
- As mentioned in the ACEI Communication [67], examine options to boost market uptake of innovative clean energy solutions through public procurement and strengthen the role that public administrations can play to support smart, clean & innovative industry & economy (DG GROW).
- Through supporting social, economic and financial innovation, enable all categories of energy end-users (individuals, companies, institutions) to assume and effectively implement their role in the increasingly decarbonised, decentralised and digitised service-based energy systems of power, transport and heat.
- Step up support to establishing a skilled, competent EU work force in new energy technologies (producers, suppliers, maintenance and repair, permitting authorities, first responders, …) (DG EMPL, EAC, RTD, GROW, …).
- Strike the appropriate balance between the conflicting aspects of protection of intellectual property and dissemination of research outcomes from publically supported R&I projects.

b) more specifically for batteries:

- ensure stable and fair access by EU industry to the supply of LIB component materials (import) and to international markets for LIB cells and packs, xEVs and ES systems produced in the EU (export) (DG TRADE).
- Critically assess the measures and the commitment outlined by European industry and Member States for efforts to better focus, coordinate and integrate their R&I efforts on batteries for e-mobility and for stationary storage applications (forthcoming Implementation Plan of Action 7 of the Integrated SET-Plan) (DG RTD, ENER, JRC, MOVE, GROW).
- Pursue the activities set out for the Battery Flagship Initiative under the recently published Mobility Package [75], covering the what-who-how of this initiative and play on the strengths of the Commission's convening power to arrive at common solutions shared between key actors in industry, public authorities, financing sector and research (SG, DG GROW, EPSC, JRC, RTD, COMP, ECFIN, …).
- Prioritise access to financing for the establishment of first-of-a-kind and pilot production lines based on the latest and best available technology.
- Together with stakeholders identify and propose measures for eliminating non-technological barriers to the use of LIBs in a number of applications.

- Ensure that the revision of the Battery Directive (2006/66/EC) and of the End-of-Life Vehicles Directive (2000/53/EC) strike the appropriate balance between environmental and competitiveness considerations and that the revisions are timely available for safeguarding and strengthening the EU competitive edge in recycling of batteries (DG ENV).
- Maintain and expand in-house test facilities for performance and safety characterisation and development of an enabling set of European standards for next generation batteries, cells and packs (JRC).
- Prepare for the inclusion of LIB related topics in the 2018 Annual Union Work Programme on standardisation; in this respect monitor the follow-up given by the ESOs to the conclusions of the JRC-organised Putting Science into Standards Workshop on batteries for e-mobility [64] (DG GROW, JRC).
- Sustain and improve the focus of R&I funding on battery chemistries (in particular for electrodes and to allow fast charging), on cell design and on high added-value manufacturing processes (DG RTD as per Annex to the ACEI Communication [67]). Next to the KLIB battery competence network [76] in Germany, the 4-year government-funded Faraday Challenge initiative endowed with £246m recently launched in UK [77] is an interesting example of structuring battery-related research over the complete value chain, with targets set on cell cost, gravimetric energy density, operating temperature range and pack recyclability to be reached by 2035.
- Maintain R&I support in order for EU industry not to lose its competitive edge in the pack manufacturing and subsequent segments in the battery value chain (DG RTD).
- Enhance synergy with other relevant EU-cofunded R&I programmes, e.g. Graphene Flagship, Smart Manufacturing, Industry 4.0 (DG RTD).

Take Away # 13

For domestic LIB cell manufacturing by European companies to be globally competitive, two conditions have to be met: the risk for private investors has to be reduced and realising economies of scale must be made possible. A set of actions that the Commission can take to enable EU industry meeting these requirements is proposed.

9 Conclusions

The Commission has been an early supporter of the development of batteries as a key enabling technology for electric mobility and for achieving Energy Union objectives on energy storage. Following their successful deployment in consumer electronics, LIBs are currently the main chemistry being pursued for these applications and this is likely to remain so for the next decade. However, the EU does not have a complete LiB value chain albeit being competitive in several of its segments: the EU is lagging on production of active materials and cell manufacture, whereas its competitive strengths reside in downstream segments (packing, applications) and in its good potential to become a global leader in recycling.

Given the growing strategic interest in batteries for achieving EU policy goals, the Commission is reflecting on the need and activities to be deployed for establishing large-scale LiB cell manufacturing in Europe for mobility as well as for stationary storage applications. To underpin future decision-making towards this, the present report has reviewed cost and market volume projections for LiBs and has looked into factors affecting EU competitiveness in the different stages of the LiB value chain. The major findings can be summarised as follows:

Economic potential for LIBs for mobility and stationary storage applications:

- The costs of LIBs continuously decrease and will soon reach a level that triggers their wide-spread, accelerated deployment in xEVs and ES applications.
- The global market for LIBs in xEV and ES applications is huge. xEVs will represent the largest market in the near future, whereas expected growth rates are highest for ES applications. Most recent market forecasts for both applications are being revised upwards.

Adequacy of existing and planned LiB cell manufacturing capacity:

- Current LIB manufacturing capacity is concentrated in Asia and is not able to meet the increasing global demand for xEV and ES. LIB cell manufacturers, in particular Asian ones, are investing in additional and new production capabilities close to the major demand centres, i.e. in Asia, US and Europe.
- The absence of domestic LIB cell manufacturing in the EU negatively affects the competitiveness of European xEV producers and ES service providers.
- Currently known planned cell production capacities in Europe are expected to suffice for meeting the minimum estimate of xEV deployment in Europe in 2025, but most likely will not be able to meet the maximum projected demand.

Scope for an EU LIB cell production activity:

- Considerations on EU competitiveness in LIB cell manufacturing should target innovation in cell chemistries, formats and manufacturing technologies/processes.
- Efforts for establishing LIB cell manufacturing capacity in the EU should primarily target LIB cells of generation-2b and beyond and should focus on production stages which are critical for LIB quality, performance and safety.
- Competing with non-EU LIB cell producers on cost-only basis is unlikely to be successful. A competitive EU LIB cell production should offer added value beyond cost, in terms of enhanced sustainability, safety and performance.

Necessary enabler for an EU LIB cell manufacturing capacity:

- Sustained and even increased R&I efforts, covering materials and manufacturing processes in terms of technical, safety sustainability performance are needed to underpin competitive battery manufacturing in the EU.

Estimation of required investments:

- Specific investment costs for new LIB cell manufacturing capacity has decreased to around $150/kWh and will further decrease as additional manufacturing capacities come on line.

Estimation of job creation potential

- Establishing a competitive LIB cell manufacturing capability in the EU is expected to create between 90 and 180 direct jobs per GWh/y production volume.

Based on these findings, the report identifies two major conditions for domestic LIB cell manufacturing by European companies to be globally competitive: the risk for private investors has to be reduced and realising economies of scale must be made possible. The report concludes by proposing a number of actions that the Commission can take to assist EU industry to meet these requirements and thereby enable it to take its share in a globally booming market.

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List of abbreviations and definitions

EV	electric vehicle
BEV	battery electric vehicle
HEV	hybrid electric vehicle
PHEV	plug-in hybrid electric vehicle
xEV	all EV classes
ES	energy storage
LIB	lithium-ion battery
SET-Plan	Strategic Energy Technology Plan
EU	European Union
DoI	Declaration of Intent (of Integrated SET-Plan Action 7)
DE	Germany
IT	Italy
JP	Japan
US	United States
KR	South Korea
PL	Poland
HU	Hungary
SE	Sweden
BG	Bulgaria
CN	China
CZ	Czech Republic
AT	Austria
UK	United Kingdom
FI	Finland
NL	The Netherlands
FR	France
ES	Spain
PT	Portugal
OEM	original equipment manufacturer
EIP	European Innovation Partnership
GWP	global warming potential
SoH	state of health
V2G	vehicle to grid
LDV	light duty vehicle
ESO	European Standard Organisations
IP	intellectual property
RED	Renewable Energy Directive
SGA	sales, general and administrative (expenses)

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Annexes

Annex I. Cost projection methodologies and results - Important points to consider

General Considerations

Scientific literature and market analysis reports contain a large number of cost projection methodologies for new technologies, incl. for LIB batteries. These methodologies are mostly based on "technology learning or experience" (e.g. [78], [79]) and express technology cost (sometimes price) as a function of factors such as annual (e.g. Fig. 3) or cumulative production, of cumulative patent number, etc. Extrapolation of the double-logarithmic relation between cost and the considered technology learning factor(s) established from historic data series allows predicting the future cost evolution.

Cost extrapolation from learning curves presents inherent limitations. A first limitation is that unforeseeable future changes (disruptive technology breakthroughs, knowledge spill-overs, changes in commodity prices, …) as well as commercial selling below cost in order to capture a market share cannot be accounted for. Second, only the learning factor(s) included in the analysis can contribute to technology cost reduction. Cost decreases from other origin which scale differently with or do not depend on cumulative production capacity (e.g. raw materials, technology progress) cannot be captured. Consequently projected technology costs monotonously decrease as the considered learning factor(s), e.g. cumulative production volume, increase and a minimum cost threshold associated with intrinsic costs does not appear in the projections[mm]. The use of S-shaped learning curves may prove more realistic in such a case [80].

In addition to considering implications from the above inherent limitations, prediction of technology cost evolution through extrapolation of learning curve(s) should be assessed cautiously, as it is affected by the number and type of learning factors considered, their range used in establishing the learning curve, the corresponding time period, the number of data in that range and period, the type of mathematical relation used for numerically fitting the data, etc. All of these affect the result of the extrapolation and it is therefore not surprising that cost evolution projections in scientific literature cover a wide range (e.g. [20], [81], [82]).

Integration of the cost versus cumulative production volume relation represented by the learning/experience curves, allows to determine the cumulative financial effort (consisting of capital investment and/or subsidy) required to achieve given cost reductions through increasing manufacturing volume[nn].

The time for reaching a given level of technology cost is obtained by introducing the future expected capacity need into a market growth model (chapter 3), from which projections of costs versus time, such as shown in Figs. 1 and 2, are subsequently derived. For such cost versus time projections, the uncertainties associated with the extrapolation of learning curves are compounded with those emanating from the market deployment scenario assumptions.

[mm] Conversion of the logarithmic axis for the learning factor into a linear axis results in horizontal asymptotic behaviour of the learning curve, suggestive of – but not actually reflecting an explicitly included - minimum cost threshold (see e.g. Fig. 3)

[nn] see e.g. JRC Scientific and Policy Report *Technology Learning Curves for Energy Policy Support* (EUR25471 EN, 2012) and SWD(2015) 142 *Investment perspectives in electricity markets*

Application to LIBs

For the specific case of Li-ion batteries, there are additional factors which affect the quality and reliability of the cost projections. One of the most important is the lack of differentiation between costs at cell, pack and system level, and indeed the lack of harmonised terminology for these levels. Another related one is the lack of differentiation between the applications considered: LIB for consumer electronics, power tools, xEVs, ES.

The above points are illustrated in the figure below, adapted from [78] which contains the most extensive data set on LIB. The data points in the figure refer to price (not cost) as a function of installed capacity (not production volume) and therefore include additional cost factors such as R&D, depreciation warranty, profit.

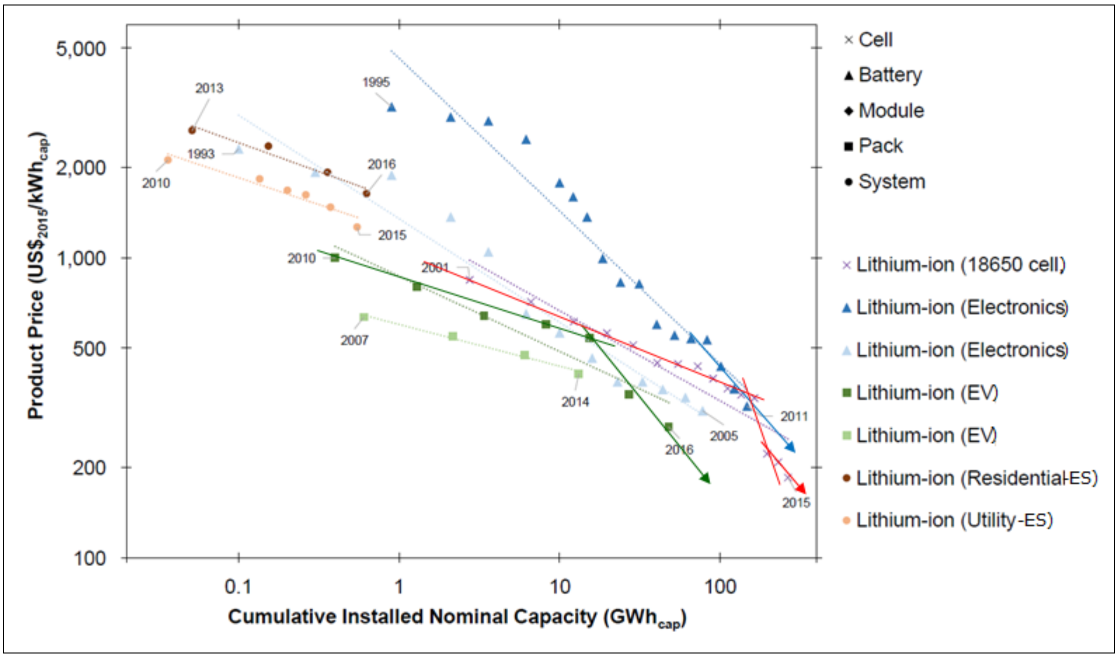


Fig. I.1: Li-ion experience curves for various technology scopes (from [78], with solid red, blue and green lines added). Note that the term "battery" is used to denote portable battery for consumer electronics and that "pack" and "system" refer to EV and ES application respectively.

Comparing the cost evolutions for cells and packs in Fig. I.1 indicates that cost reductions for EV and ES batteries can be mainly attributed to decreases in cell manufacturing costs and to a lesser extent to cost reductions of additional components required for the packs. Extrapolating to a cumulative capacity for EV packs of 100 GWh (green arrow, corresponding to one of the two literature sources for EV-data considered in the figure and assuming similar high learning rates as observed for high-volume production of Li-ion portable batteries and cells shown by the blue and red arrows) reveals a price of $170/kWh, whereas $100/kWh is reached for a cumulative capacity of ca. 240 GWh.

For the above example (based on a high learning rate), the cumulative financial effort required to achieve given cost reductions through increasing manufacturing volume is shown by the solid blue curve in Fig. I.2, where the labels correspond to the cumulative manufacturing volume and the year by which this volume is reached (taken from Fig. 8). The figure also shows the contribution of the cost of cell materials from [79], which is assumed not to depend on manufacturing volume and acts as a lower cost threshold for the packs.

Fig. I.2 shows that starting from the 2016 price of $332/kWh for a EV pack production volume of 33 GWh (see Table 1), the financial effort required to reach a target price of $100/kWh corresponding to a cumulative pack production volume of 240 GWh, amounts to 33 B$[oo].

For a given manufacturing volume, subtracting the sales income from the required cumulative financial effort results in the cumulative financial spend required to manufacture (and deploy) a defined number of packs at a given price. If, e.g. consumers were prepared to pay a price of $100/kWh, the financial effort required from manufacturers to reach $100/kWh target price could be reduced nearly threefold from 33 B$ to 12 B$ (red curve in Fig. I.2). Similarly, for a pack price of $70/kWh charged to the customer, the required financial effort is nearly halved and decreases to 19 B$ (orange curve)[pp].

Conversely, Fig. I.2 shows that a cumulative budget envelope of 10 B$ enables manufacturers to reach a manufacturing cost of about $208/kWh, down $124/kWh from the current cost of $332/kWh, by more than doubling the cumulative production volume from 33 GWh to 70 GWh. Taking into account sales income generated from a sales price of $70/kWh, this cost is further reduced to $173/kWh, for a correspondingly larger cumulative production of about 100 GWh.

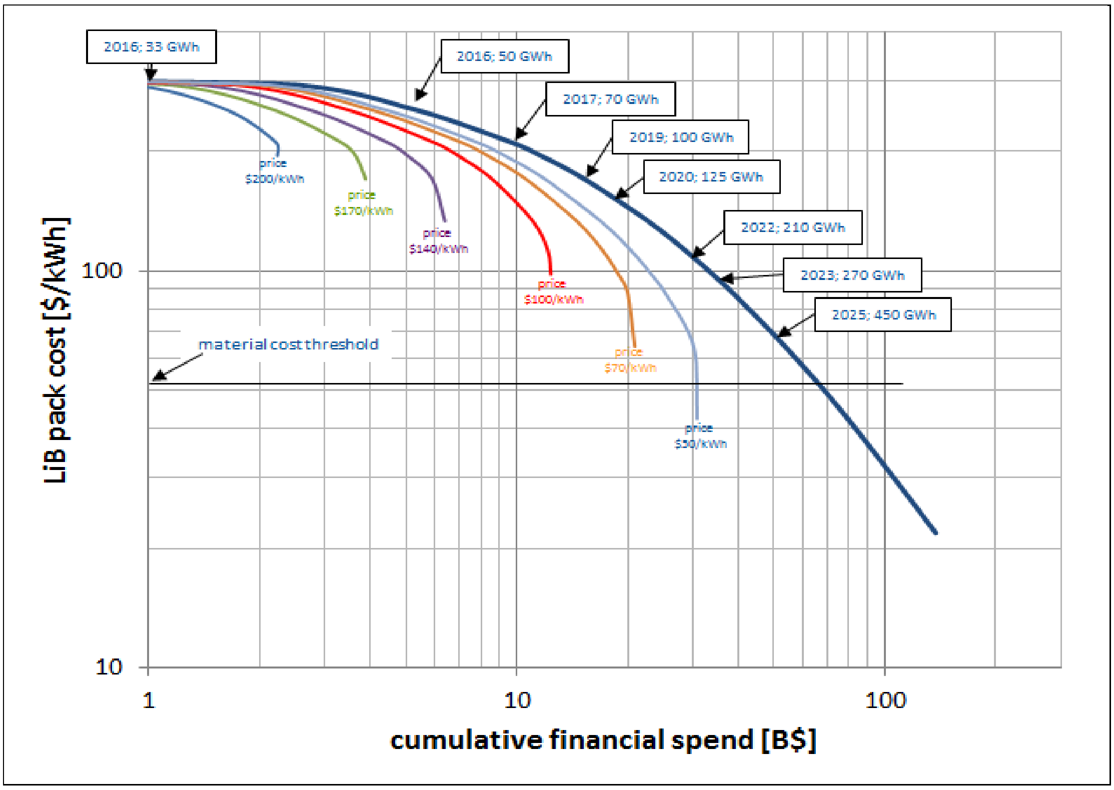


Fig. I.2: Cumulative spend (horizontal axis) required for establishing manufacturing capability (labels) to produce LIB packs at a given cost (vertical axis). Individual curves correspond to a selected fixed price charged to the customer. The year number associated to a given cumulative capacity is taken from the optimistic demand scenario in Fig. 8.

oo Assuming a 1:1 conversion $:€, the 2030 target from the DoI of 75 €/kWh requires a financial expenditure of around 46 B€ corresponding to ca. 390 GWh cumulative production volume in the EU by that time.

pp When fixed sales prices are assumed in the analysis, a vertical asymptote in Fig. I.2 is approached when costs on the vertical axis approach the sales price.

The projected evolution of LIB pack cost versus time derived from Fig. I.2 is shown in Fig. I.3, which also includes the most recent cost projections from other sources. The figure illustrates that cost estimates have been revised downward in the last two years. It also shows that the cost projections based on extrapolation of the learning curve shown in Fig. I.1 (green arrow, i.e. high learning rate) and on the optimistic demand scenario (Fig. 8) fall within the range corresponding to these updated lower cost estimates. Finally, the cost targets of the DoI seem to be quite realistic (assuming a 1:1 conversion ratio from € to $).

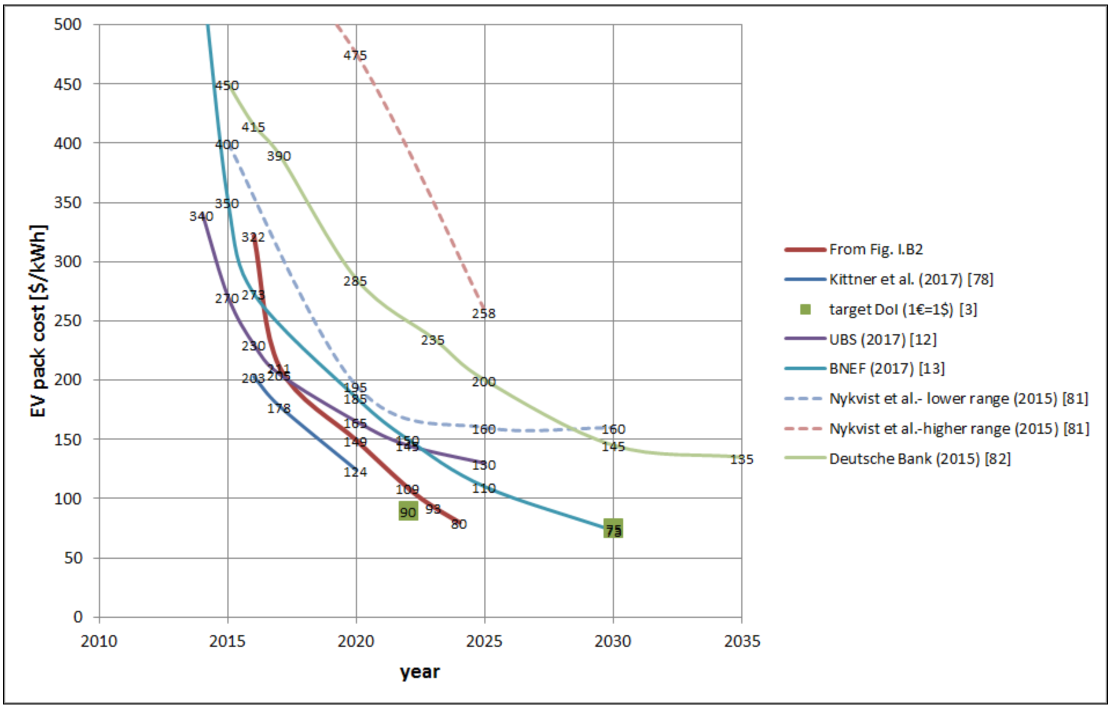


Fig. I.3: Cost evolution for EV LIB packs compiled from a number of sources (labels represent actual costs). The dashed curves represent upper and lower values of the projected cost range in [81].

Annex II. Manufacturing innovation for higher efficiency and quality at reduced costs

Technology innovations in the LIB manufacturing process should target achieving the opportunities for EU competitiveness identified in Chapter 5. Next to implementing improvements in the individual production steps resulting from R&D (e.g. [76]), this can be realised by (1) production scale-up, (2) higher stability of the manufacturing process, (3) building in flexibility, while simultaneously paying due attention to additional considerations with respect to added value beyond cost (section 5.3).

1. Production scale-up

Increasing the production volume can be achieved through multiplication of production lines or through increasing the production volume of the line, i.e. scale-up. A higher production volume is usually associated with reduced throughput time. Scale-up is the major enabler of technology-learning which contributes to manufacturing cost reduction (see Annex I).

2. Increased yield

For a given throughput volume, increasing the stability of the production process, e.g. through automation, results in less rejected products and thus higher yield. Also higher integration of electrode and cell manufacturing process steps contributes to increased yield by reducing the possibility for electrode contamination, as does the use of high speed in-situ non-destructive inspection techniques for quality control to detect flaws and internal short circuits. Process stability also benefits from increased use of automation in production scale-up.

3. Flexibility in manufacturing

Whereas measures for scaled-up and more stable production processes are not specific to the manufacture of LIB cells, higher flexibility in production definitely is, and needs to consider the different aspects of battery chemistry, format (e.g. cylindrical, prismatic, pouch) and size:

The production of generation-3 LIBs for BEV does not require drastic changes to the production processes used for generation-2 cells. Rather it requires adaptations to process parameters or modifications in individual parts of the manufacturing chain to be able to deal with different materials for cell components (e.g. high-Ni cathode, Si-based anode, high voltage liquid electrolyte). Additionally, modifications may be needed for reaching requirements for higher-power cells. Process modifications may cover e.g. water-based coating, high speed coating and stacking, … and should also consider the possibility to deal with different cell formats and sizes: larger cells enable quality-optimised handling of thin sheet material, which combined with a greater thickness of active materials, results in higher energy densities and fast charging ability. Use of large format cells may also benefit battery pack manufacturers (incl. OEMs) due to lower complexity (fewer connections, simpler thermal balancing system, simpler electronics).

Production of generation-4 and 5 cells will require more substantial changes to the production process, particularly for processing and coating of electrode materials and for manufacturing of solid electrolytes. For these chemistries no known significant manufacturing base has yet been developed by any Asian LIB manufacturer[qq]. This provides an opportunity for Europe to break-in to cell manufacturing for these chemistries.

The needed flexibility for handling chemistries of both generation 3 and subsequent generations with different cell sizes and formats can be achieved in two ways:

- Dual line design: one (larger) line is used for production of batteries with conventional chemistries and formats, while a second flexible line allows introduction of new materials/techniques/formats that can be scaled up quickly when needed.
- modular design plants, whereby modules connected in series in the overall production line, can be individually exchanged, modified and/or expanded.

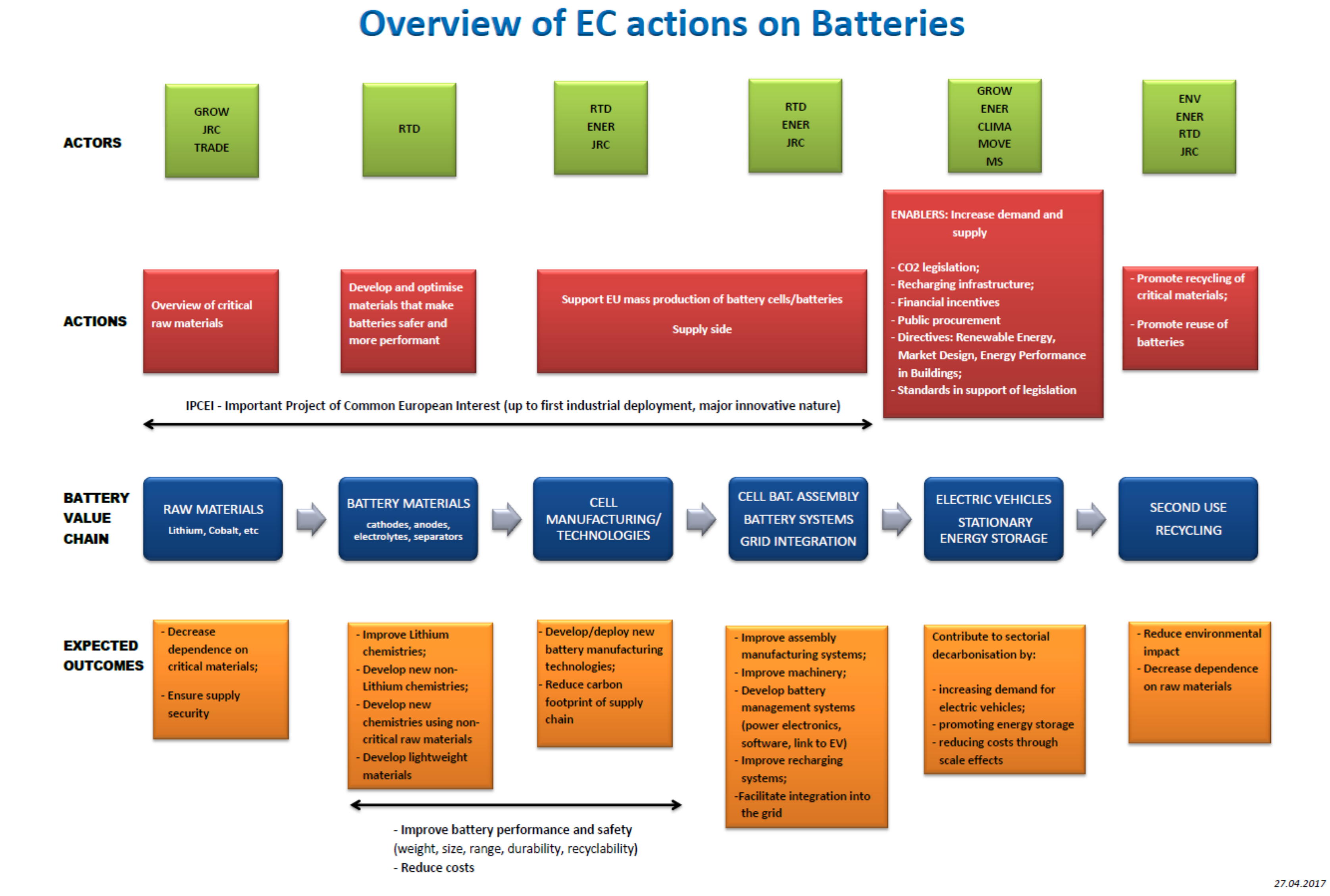
All the above measures should not jeopardise efforts to increase the efficiency of the overall cell manufacturing process in terms of the inter-related parameters of time, costs and quality. A number of areas in particular merit attention [56]:

- Acceleration of formation and ageing of battery cells to reduce process time and associated storage periods and thereby reduce the impact of high capital costs.
- Reduction of the size of dry (humidity-controlled) clean rooms needed for reducing possibilities of contaminant ingress during electrode coating, drying, calendaring, electrolyte filling, and cell assembly, including cell sealing
- Designing cells (format, size, manufacturing processes, labeling) so that their constituent materials can easily be recycled.

All of the above evidently benefit from implementation of the opportunities offered by "Manufacturing 4.0": e.g. the ability to deal with vast data volumes in the production process, new forms of human-machine interaction, advanced robotics and 3-D printing, new and increased capabilities for traceability of process parameters, etc.

[qq] Note however the recently announced Toyota effort into using solid-state LIBs for their xEVs as of 2022.

Annex III. Overview of EC activities on batteries structured along the value chain



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