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Li-ion batteries for mobility and stationary storage applications

Scenarios for costs and market growth

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Contents

Abstract

Li-ion battery costs could decrease rapidly, by at least 50 % in 2030 and up to 75 % in 2040, due to learning from mass production driven by electric vehicles. Stationary storage systems may benefit from somewhat slower yet substantial cost reduction of 65 %. Market barriers or inaction on climate goals can affect these trajectories.

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Executive summary

Recent cost reduction of Li-ion batteries raise the expectations that electric vehicles and energy storage at grid and/or household level will become cost-competitive and will penetrate the respective markets in great numbers. Based on announcements, the global Li-ion cell manufacturing capacity is expected to quadruple or even increase six times by 2021 – 2022 compared with 2017 levels. By 2040, 150 to 900 million electric vehicles are projected to be on the road, which is two to three orders of magnitude higher than today. Over the same period, stationary storage may reach up to 1 300 GWh, compared with about 3 – 4 GWh installed front-of-the-meter today. These projections point towards a potentially significant market growth of Li-ion batteries, but also towards a range of views on the magnitude of these developments. While in the near-term the global manufacturing capacity is set to increase, in the longer-term the range of projections is wide. The projections depend on the direction the world will take, for example, in view of action against climate change by decarbonising road transport. As such, cost trajectories of Li-ion batteries may be influenced by the total deployment levels of electric vehicles and stationary storage due to economies of scale, and by the cumulative manufacturing experience gained globally.

Focusing on Li-ion batteries as the family of batteries for mobility and stationary storage applications of today and the near future, this report contextualises their potential cost trajectories in line with global production scale, based on three different scenarios for the global energy system up to 2040 (*high, moderate* and *low*).

EU policy context

The EU is transitioning to a secure, sustainable and competitive energy system as laid out in the European Commission's Energy Union strategy. Li-ion batteries are often seen as the technology that can help decarbonise transport, lift the penetration levels of intermittent renewable energy (wind and solar) and offer a competitive edge to the EU industry in the Li-ion battery value chain. Batteries, including Li-ion, are recognised as a key enabling technology for the energy transition of the EU under the Energy Union and as such, they are specifically mentioned in several policy initiatives that address transport, raw materials and energy economic sectors, EU industrial policy and EU Research and Innovation. The strategic importance of batteries for the EU is further demonstrated by the formation of the European Battery Alliance and the adoption of the Strategic Action Plan for batteries as an integral part of the third 'Europe on the Move' package. Li-ion batteries also link with the European Commission's actions on raw materials, namely the Raw Materials Initiative, the European Innovation Partnership on Raw Materials and the assessments on Critical Raw Materials.

Main findings and conclusions

By 2040, according to key projections, the global annual sales of Li-ion batteries increase to around 4 TWh in the *high*, 2 TWh in the *moderate* and 0.6 TWh in the *low* scenario. This corresponds to about 110, 55 and 15 operational gigafactories in each scenario, respectively, assuming 35 GWh annual production capacity for each gigafactory. For comparison, the sales volume in 2017 was about 60 GWh.

These projections entail that by 2030, Li-ion electric vehicle battery packs could come at least at half the cost of today's production (100 €/kWh instead of about 200 €/kWh today) due to mass production. By 2040, the cost could drop an additional 50 %, ultimately reaching 50 €/kWh. Such trajectories are feasible based on costs of new Li-ion cathode chemistries and other battery pack materials that are estimated at around 30 €/kWh (other additional costs are estimated at around at 10 – 20 €/kWh). Meeting policy goals such as the Strategic Energy Technology Plan (SET Plan) cost target of 75 €/kWh is feasible in both *high* and *moderate* scenarios (which entail fast ramp-up of Li-ion manufacturing capacity, of about 2 gigafactories globally per year until 2030).

Cost reduction of Li-ion battery packs for electric vehicles spills over to stationary storage systems, but cost reduction in this sector occurs somewhat slower due to the contribution of other major cost components (e.g. inverters, balance of system hardware, soft costs such as engineering, procurement and construction). The benchmark costs of Li-ion stationary storage systems in 2017 were about 500 €/kWh for energy-designed systems, about 800 €/kWh for power-designed systems, and 750 €/kWh for residential batteries (1). Ultimately, by 2040, stationary storage system costs will range between 165 and 240 €/kWh for energy-designed utility-scale systems, between 280 and 410 €/kWh for power-designed utility-scale systems and between 250 and 365 €/kWh for households. Lowering of balance of system and other soft costs can potentially help further cost reduction of stationary energy storage systems, lifting barriers for their widespread deployment. The SET Plan target on investment costs for stationary storage at a system level at 150 €/kWh (2) could be attainable at high global deployment of EVs and more than 1 TWh of stationary storage. These findings are influenced by the assumed learning rates, the assumption that cost reduction from Li-ion battery packs for EVs spills over to stationary storage systems, and on whether aged batteries from transport are repurposed to storage at a portion of the price of a new battery pack. Other assumptions, such as the evolution of the battery size or the battery lifetime were not found to influence significantly the cost projections based on learning.

The main messages to take away from this analysis are the following:

- Wide-spread deployment of electric vehicles will lead to a rapid decrease of Li-ion battery costs in the near term.
- Investment costs of Li-ion battery stationary storage systems will decrease, yet improvements should focus also on non-battery pack system components.
- European manufacturing of Li-ion battery cells will increase its share in global production, provided that announced plans materialise. Supplying domestic demand may prove challenging if capacity does not ramp up after 2025.
- Re-using and repurposing of Li-ion batteries to energy storage applications after their end of life in electric vehicles contributes to further cost reduction.

Related and future JRC work

This report complements a series of other JRC publications on key issues related to Li-ion batteries, namely the competitiveness of the EU in the Li-ion battery sector and opportunities for Europe in the Li-ion value chain. Future work could relate with economic assessments to complement modelling activities on the feasibility of energy storage or other economic metrics such as levelised costs, lifecycle costs and so forth.

Quick guide

This report is structured as follows: Chapter 1 introduces the policy context around Li-ion batteries, their relevance in the energy transition and the knowledge gaps on deployment and costs. Chapter 2 continues with an overview of historical developments of Li-ion batteries markets and costs, focusing on EVs and storage. Chapter 3 presents near-term expectations and long-term projections for growth and costs of Li-ion batteries based on

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(1) Batteries for stationary storage are used for a range of applications with some being more suited to store energy and others to supply power. In the present report, batteries that can provide energy for more than 1 hour are called *energy-designed* and batteries that can provide energy for less than 1 hour are called *power-designed*. Smaller scale r*esidential* batteries provide energy for more than 1 hour and do not require system integration components. The cost structure of these batteries is different both per kW and kWh.

(2) The SET Plan target for stationary energy storage reads: "For stationary energy storage the SET-Plan R&I will aim at developing and demonstrating technology, manufacturing processes, standards and systems, which have the potential of driving high-efficiency (>90%) battery based energy storage system cost below €150/kWh (for a 100kW reference system) and a lifetime of thousands of cycles by 2030 to enable them to play an important role in smart grids" [23]. Although only the investment cost is cited here and hereafter, it is imperative to consider it in conjunction with the requirements on efficiency, power rating and lifetime.

literature. Chapter 4 provides estimates on scenario-based cost trajectories for Li-ion batteries for mobility and stationary storage applications based on the learning curve method. Chapter 5 draws the final conclusions of the analysis.

1 Introduction

The EU is transitioning to a secure, sustainable and competitive energy system as laid out in the European Commission's Energy Union strategy [1]. Energy storage, and in particular batteries, is frequently addressed as the technology that may unlock the transition to a decarbonised and clean energy system due to their potentially broad application in the power sector and in transport [2–4].

In the proposed "Clean Energy for all Europeans" legislative package, the EC sets global leadership in Renewable Energy Sources (RES) as a priority for the EU (COM(2016) 860 final; [5]). To achieve this goal and deliver on international climate change mitigation commitments [6], at least 32 % of energy supply must be sourced by renewables as agreed by the European Parliament and Council [7]. The **power** sector, however, could be technically challenged by high supply of electricity from intermittent RES, even more so as costs of wind and solar decrease, making them more appealing to the market [8–11]. Wind turbines and photovoltaics generate electricity when the resource is available, but not necessarily when electricity is needed. At the grid level, batteries offer an electricity storage option that can moderate the variability of intermittent RES and increase their share. They do so by providing reliable grid services (e.g. peaking capacity, frequency and voltage control, peak shaving, congestion management, black start), which become increasingly important in the face of baseload fossil fuel-based assets phasing out. In behind-the-meter applications, batteries improve power quality, reduce demand charge, and increase the reliance on self-generation. In integrated systems supported by smart market designs, batteries may contribute to decentralisation and the shift of consumers to prosumers, thereby empowering the participation of the EU citizens in the energy market as envisaged in "Clean Energy for all Europeans" legislative package [5].

Transport is a highly contributing sector in the EU that has been witnessing growth in greenhouse gas emissions [12]. Road transport accounts for about 73 % of all greenhouse gas emissions in transport [12]. Together with low-carbon options such as hydrogen or advanced biofuels, the deployment of Electric Vehicles (EVs) at large scale seems to be a prerequisite in order to transform the sector to a low-emission activity. For a safe, clean and connected mobility, the EC promotes electro-mobility and communicates the significance of batteries in the sector's clean energy transformation and in the competitiveness of the EU's automotive industry with the "Europe on the Move" and "Delivering on low-emission mobility" packages (COM (2018) 293 final, COM (2017) 283 final, COM (2017) 675 final); [13–15]). The important role that batteries will have in a modern and competitive automotive EU industry is acknowledged in the 2017 "A renewed EU Industrial Policy Strategy" communication (COM (2017) 479 final; [16]).

Batteries also stand at the interface of power and transport supporting their **sectoral integration**. In the longer term, coupling these sectors may introduce cost efficiencies in the system and help bring their emissions closer to zero [17,18].

For anticipated boosted future demand for Li-ion batteries the sustainable and secure supply of **raw materials** (e.g. lithium, cobalt) is of strategic importance for the EU. Scenarios on market growth of Li-ion batteries therefore also link with the European Commission's actions on raw materials, namely the Raw Materials Initiative [19], the European Innovation Partnership on Raw Materials [20] and the assessments on Critical Raw Materials [21].

The EU's Research and Innovation agenda on batteries is set in the frame of a dedicated Key Action of the Integrated SET Plan (C(2015) 6317 final; [22]), where the Declaration of Intent defines targets for performance, cost, recycling and manufacturing of batteries and the Implementation Plan outlines the research actions and priorities to meet the agreed targets [23,24]. The strategic importance of batteries for the EU is further demonstrated by the formation of the multi-stakeholder group "European Battery Alliance" [25] and the adoption of the Strategic Action Plan for batteries as an integral part of the third 'Europe on the Move' package.

One of the barriers that delay the large scale deployment of batteries, and especially of lithium ion (Li-ion) batteries, is their high capital investment costs. Even though Li-ion battery prices fell almost 80 % since 2010 [26] they remain substantial. In the power sector investment costs of stationary storage systems are still too high to justify a business case, partly owing to the market design [27,28]. Similarly, although the uptake of photovoltaics in households has been increasing, their integration with home battery systems is limited and so far driven by preference for self-sufficiency rather than decisions on return on investment [29,30]. In transport, upfront and total costs of ownership of EVs are still high; more than 50 % of EV costs are attributed to battery packs [31]. However, with strong government support in some countries, the total cost of ownership of EVs is already in parity or even lower, compared to internal combustion engine vehicles [32,33]. Depending on oil prices, taxation policy and use profiles, studies expect that EVs will reach cost parity with internal combustion engines in most regions by mid-2020 towards 2030, should battery costs decrease [26,31].

Targeted EC policies recognise that costs need to decline for mass adoption of batteries in mobility and stationary storage applications. For example, the development of affordable and integrated energy storage solutions is a priority area stated in the "Accelerating Clean Energy Innovation" communication [34], and cost reduction has been the subject of several EU-funded projects [35]. Moreover, the "Declaration of Intent of SET Plan Key Action 7" sets a target of 75 €/kWh for a battery pack for automotive applications and 150 €/kWh for stationary storage applications at a system level by 2030 [23] ([3]). The aim of these policies is straightforward: to help the EU become the global leader in sustainable battery production and use.

Dynamics of the Li-ion battery sector –currently the fastest growing battery type– outside the EU, however, exerts a significant influence on technological progress, innovation and costs. While the EU has strong presence in downstream segments of the value chain (e.g. battery pack assembly, recycling and re-purposing) [36], slightly less than half of the battery pack costs lie in cell manufacturing [26,37], where the position of the EU needs to be strengthened. The existing and announced manufacturing capacity of Li-ion cells is mainly in Asia (China, Japan and South Korea) [26,36]. Besides manufacturing capacity, Asian countries now also have the lion's share in EV sales, reaching about 55 % of global sales in 2017 [38]. Under existing or near-term market conditions this trend could continue, as more than one-third of the global EV fleet is projected to be deployed in China and about one-fifth in Europe by 2040 [26]. Moreover, the size of the EV market strongly depends on the global action required to meet agreed climate goals. Based on existing policies, the global EV stock could reach 60 million cars in 2030, yet this projection could more than triple should climate goals below the 2 ^{o}C target be attained [31]. Differences in market share are even more pronounced on batteries for stationary storage. By 2040, about 30 % of the global capacity may be installed in China while slightly more than 10 % in Europe [39].

With these possible developments ahead, future costs of batteries may ultimately depend on the scale and the cumulative manufacturing experience gained globally, a relationship that has been empirically observed for several other technologies [40,41]. Despite the plethora of assessments on how Li-ion battery costs may develop, they do not always capture one or more of the following aspects: a) due to synergies or competition, the market and production rate for batteries also depend on deployment of other technologies in the energy system (e.g. residential photovoltaics), RES or climate change mitigation goals, b) system costs of batteries for stationary storage may benefit from innovations and production scales of battery packs for EVs, as they use similar or the same electrochemistry, materials and manufacturing process, c) recent cost reductions in

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([3]) Taking into account the cost of electrochemical modules, the cost of the inverters and power electronics and the installation and integration costs. This target refers to high efficiency (>90 %) battery-based energy storage system (100 kW reference system) and a lifetime of thousands of cycles by 2030. SET Plan Key Action 7 has a separate cost target for stationary applications per cycle. This target is not assessed in the present report.

batteries have not been included in frequently cited price forecasts, and as shown in the case of RES technologies, effects could be substantial [42]. Energy system models that are used for assessments of policies and technologies ([4]) so far rely on cost trajectories that have paid limited attention to these aspects. As such, their results and the information provided to policy makers may be influenced to the extent they relate with battery costs. These are caveats that need to be addressed to inform the EC policy process.

Focusing on Li-ion batteries as the family of batteries for mobility and stationary storage applications of today and the near future, this report contextualises their potential cost trajectories in line with the global production scale based on different technology developments in the energy system and scenarios up to 2040. This report complements a series of other JRC publications on key issues related to Li-ion batteries, namely the competitiveness of the EU in the sector [43] and opportunities for Europe in the Li-ion value chain [36].

([4]) Examples of such models are PRIMES [124], POTEnCIA [125] and JRC-EU-TIMES [126].

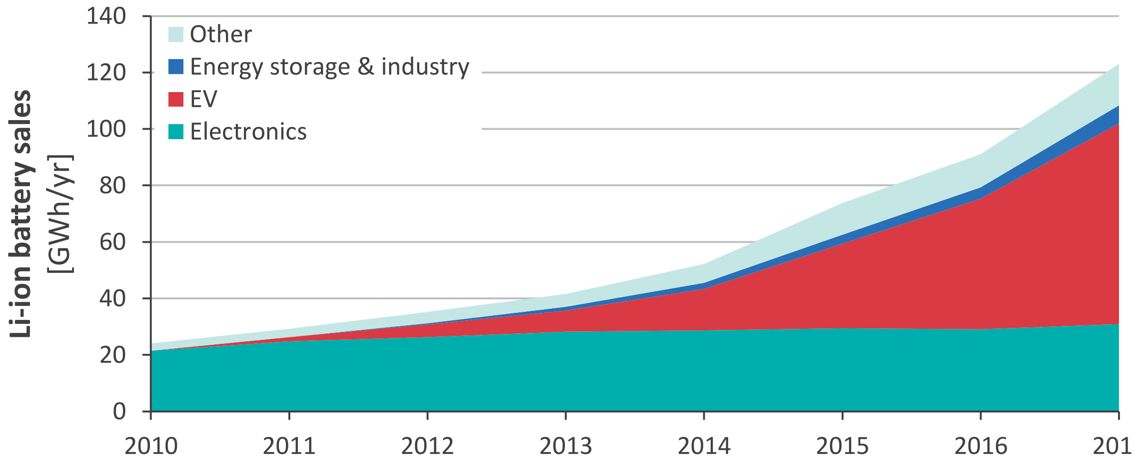
2 Current situation of Li-ion battery markets and costs

2.1 Li-ion battery markets

Since their introduction into the mass market in 1990, Li-ion batteries have been used in applications such as electronics, medical devices and power tools. By 2010, their total market volume increased one order of magnitude (from about 2 to 20 GWh), reaching a total annual market value of about 6.5 bn € largely owing to portable electronics [44]. From 2010 onwards Li-ion batteries have been growing annually at 26 % in terms of production output and 20 % in terms of value ([5]). In 2017, the total market size of Li-ion batteries was about 120 GWh (24 bn €).

The electronics market gradually slowed down, as indicated by the observed 6 % annual growth in 2010 – 2017 (Figure 1) and is expected to saturate further as shown by near term forecasts (section 3). Despite the saturation of the electronics market, the sales of Li-ion batteries continued to grow primarily due to the staggering demand from EVs, the niche yet fast growing industrial and stationary storage applications, and the slower but substantial growth and size of other markets such as electric bikes (Figure 1). Within four years since their introduction, annual sales of Li-ion batteries for EVs surpassed those for electronics. They have been witnessing an average year-over-year growth of 67 % and these trends are expected to continue (section 3). Li-ion batteries for stationary storage begun to emerge in large market volumes around 2011 and since then their total installed capacity increased rapidly to reach about 2 GWh in 2017 [26]. With the penetration of renewable energy increasing, Li-ion battery sales for stationary storage may grow even faster (section 3). Overall, the market share of Li-ion batteries for EVs and stationary storage increased from about 5 % early this decade to more than 60 % in 2017.

Figure 1 Global historical annual growth Li-ion batteries in main market segments



Source: JRC based on Avicenne Energy [44]. *Note*: Data include sales and stock. *Electronics* includes mainly portable electronics, *EV* include BEV, PHEV and electric buses, *Energy storage & industry* includes stationary storage, UPS, telecom, and applications in industry, *Other* includes medical devices, power tools, electric bikes and gardening tools.

2.1.1 Electric vehicles

More than 3 million passenger light duty EVs were on the road in 2017 (Figure 2), which represent about 0.2 % of the total global passenger car fleet [26,45]. Cumulative sales, of EVs including electric buses surpassed 4 million in mid-2018 [46]. Since their

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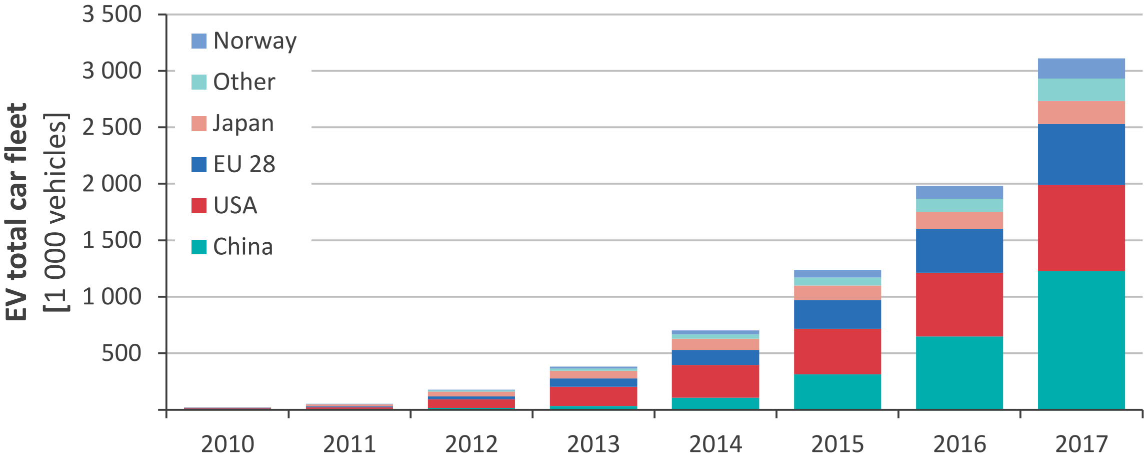
[5] Compound annual growth rate.

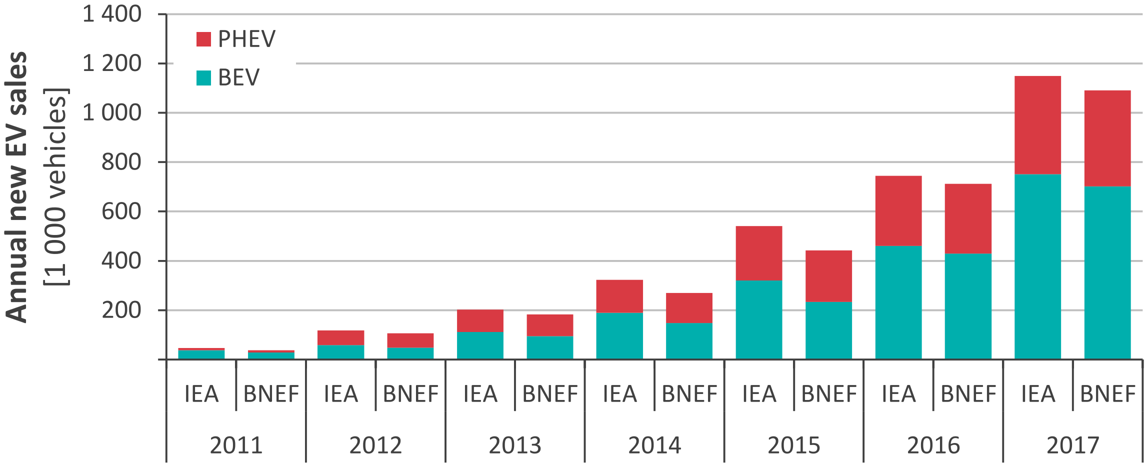
introduction to the mass market in 2010, the annual sales of EVs exceeded 1 million cars for the first time in 2017 (excluding non-plug in hybrid electric vehicles; Figure 3). Battery Electric Vehicles (BEV) represent two-thirds of total EV sales globally (Figure 3). In specific markets, however, such as in Japan, Plug-in Hybrid EVs (PHEV) have the lion's share (two-thirds of new sales). In the EU, BEVs and PHEVs are currently sold annually in roughly equal amounts [38,47,48]. The EU represents a sizeable market (15 % of new EV sales in 2017), but more than 50 % of new EVs are nowadays sold in China.

Figure 2 Total global EV fleet (excluding electric buses) in different regions in 2010 – 2017



Source: JRC based on IEA [45]. *Note:* EU 28 represents the markets of Finland, France, Germany, the Netherlands, Portugal, Sweden and the UK.

Figure 3 Annual new EV sales per EV type (BEV or PHEV)

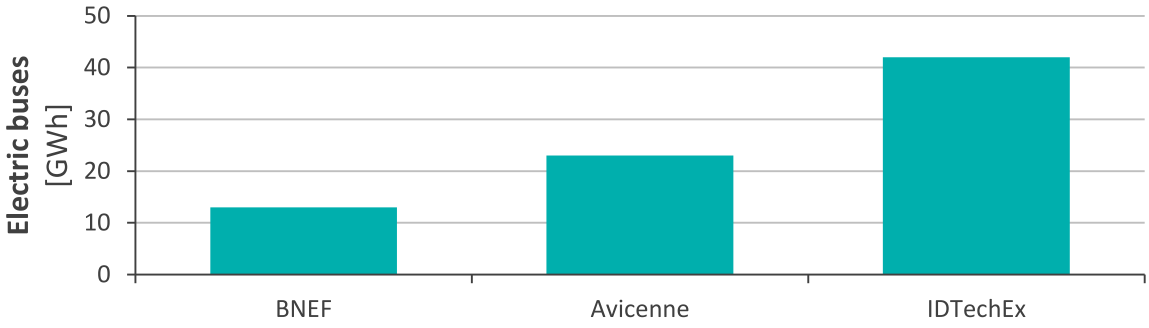


Source: JRC based on IEA [45] and BNEF [38].

Electric buses are a market segment of EVs that is quickly gaining market share, especially in China [26]. A fleet of about 386 000 electric buses in 2017 is reported, which is roughly 10 % of the global EV fleet [26]. In mid-2018 the cumulative sales of electric buses reached 421 000 [46]. About 97 % of electric buses and 75 % of their batteries are currently produced in China [49]. Electric buses have large battery capacity (60 to 550 kWh [50]), and their demand for Li-ion batteries is sizeable and comparable with that of passenger light duty EVs (Figure 4).

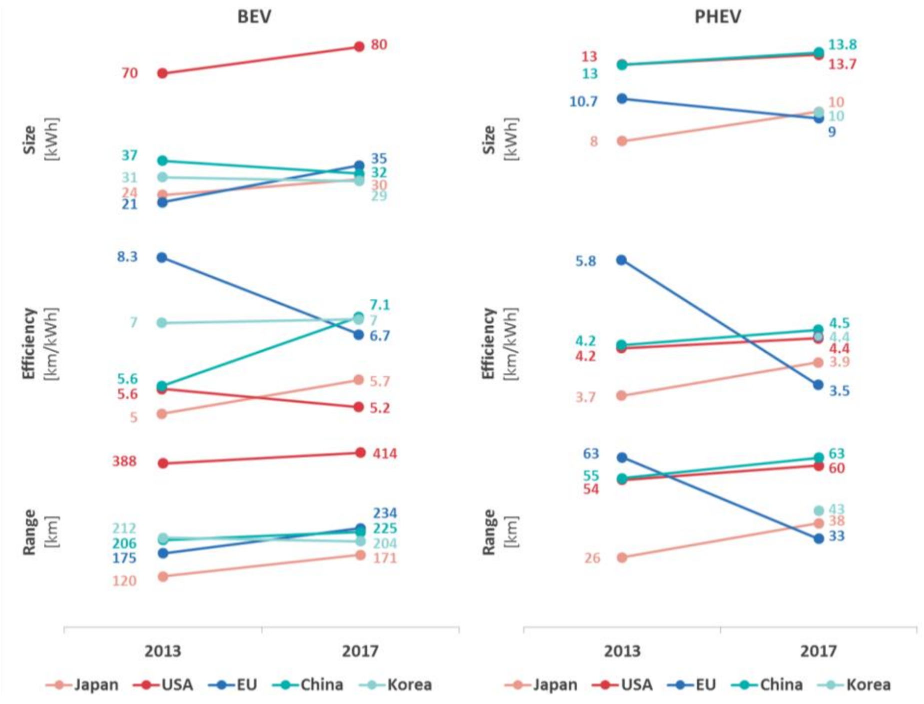
Based on annual sales, the weighted average battery capacity of BEV is around 39 kWh and of PHEVs around 11 kWh. The EV performance characteristics vary depending on the producer (Figure 5). On BEV, US producers clearly stand out due Tesla vehicles, which have large-sized batteries (75 to 100 kWh depending on the model) and consequently long range. In terms of efficiency (6), however, Chinese and Korean manufacturers are leading as they focus on producing lighter vehicles. PHEV manufacturers focus on different properties as shown, for example, by the low range and efficiency of vehicles produced by EU companies which are more power-oriented (e.g. acceleration of roadsters, load of sport utility vehicles (7)) compared with Chinese PHEVs.

Figure 4 Li-ion battery demand for electric buses in 2017/2018



Source: JRC based on different literature sources [47,51,52]. *Note*: Avicenne Energy data include sales and stock in 2017 [47]. IDTechEx data represent their forecast for 2018 [52].

Figure 5 Weighted average performance of BEV and PHEV based on sales in 2013 and 2017 per producer



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(6) Defined as km/kWh.

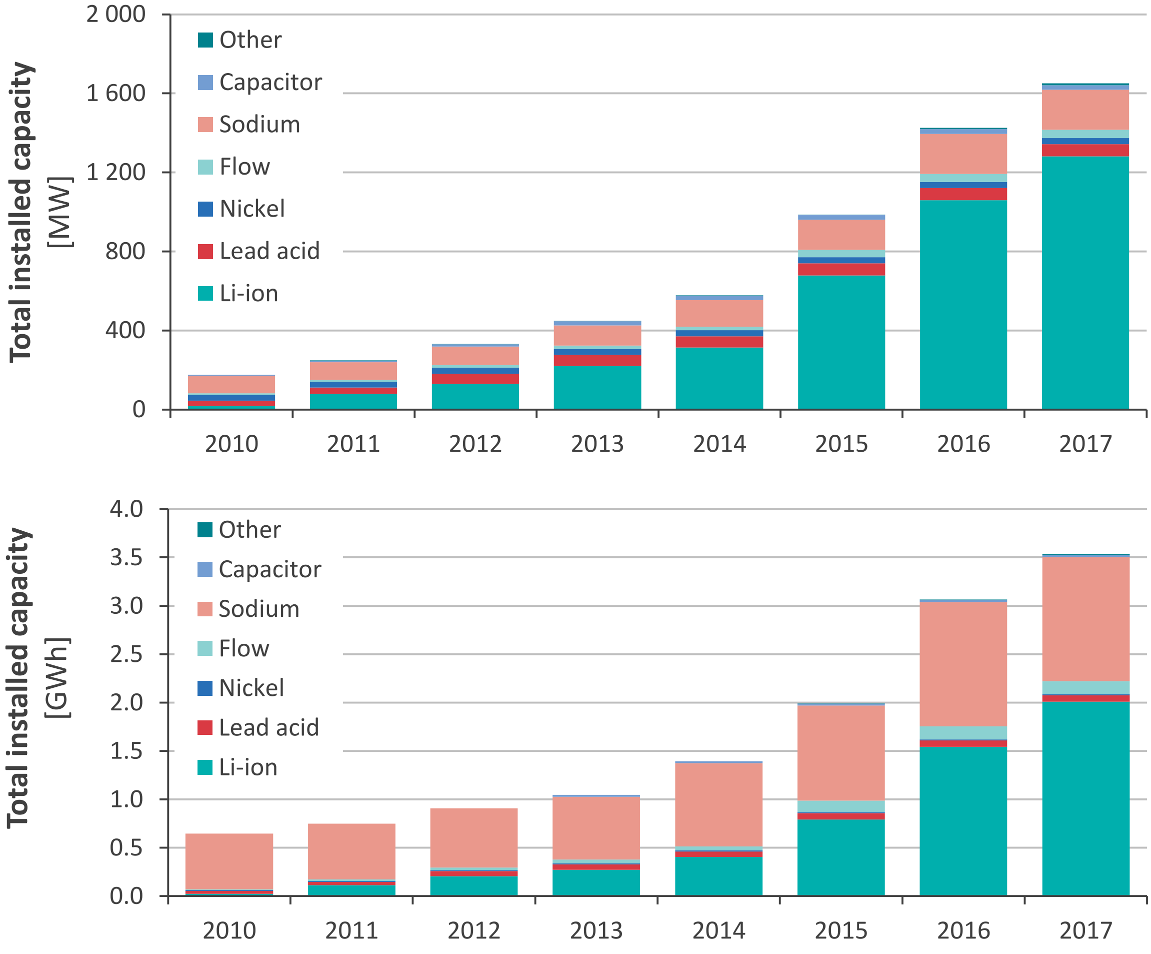
(7) Notably, the efficiency drop of EVs between 2013 and 2017 made by EU producers, is attributed to the increase in the share of sales of BMW i3 in 2017, which has larger battery capacity but lower range compared to Renault Zoe ZE sold in 2013. Similarly, the efficiency drop of PHEVs is due to the shift of sales concentrated to Volvo V60 and Opel Ampera in 2013 to a diverse set of PHEV models in 2017 such as BMW 330e, xDrive40e, Volkswagen Passat GTW, Audi A3 e-tron, etc.

Source: sales data from BNEF [38] and technical specifications from WattEV2Buy [53], High Edge [54] and ITRI [55]. *Note*: country grouping based on headquarter location of the producer (see Annex 1 for classification of producers per country). Sales data include models that sold more than 8 100 since 2011 (i.e. 93 % of total light duty EV sales).

2.1.2 Stationary storage

In 2017, global capacity of stationary storage exceeded 1.5 TWh (160 GW) [56]. The vast majority of installed capacity is pumped hydropower (more than 98 %). Electrochemical system storage is about 1.6 GW (2.8 bn €) and Li-ion batteries are the main type used (8), accounting for about 1.3 GW (0.85 bn €) or 81 % (in terms of power capacity) of all electrochemical system storage in 2017 (Figure 6). The total battery energy storage market value is roughly equally divided between lead-acid, li-ion and other battery technologies. Since their large-scale introduction in 2011, the sales of Li-ion batteries for stationary storage have witnessed an overall growth, although sales have not been following a constant increase, as shown by the drop between 2016 and 2017 (Figure 7). Nonetheless, Li-ion batteries for stationary storage applications are by far the technology with the strongest growth and market share compared with other electrochemical energy storage options.

Figure 6 Global cumulative installed capacity of electrochemical system storage



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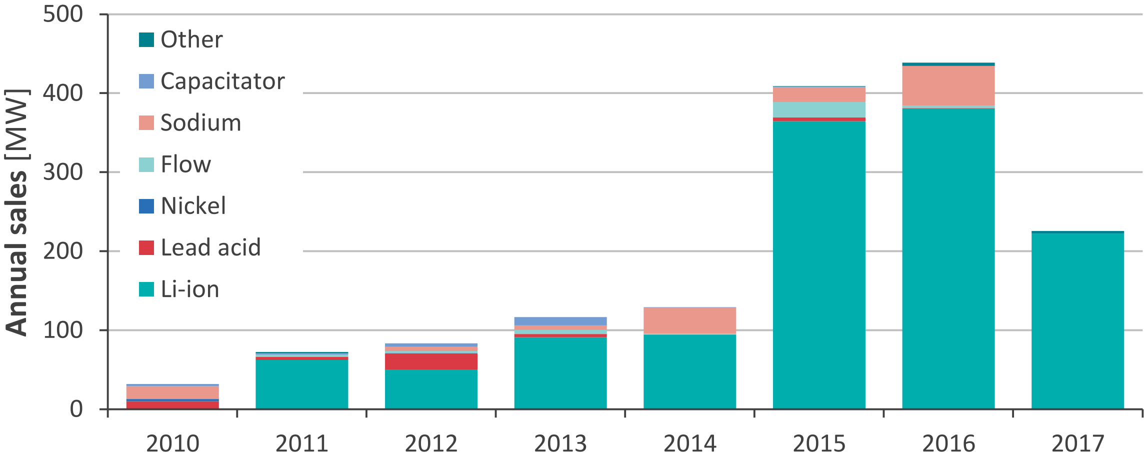
(8) A third of rated power capacity of sodium-sulphur batteries is built in Japan, including a large-scale facility of 50 MW/300 MWh built for arbitrage, in 2016. Sodium-sulphur batteries are characterised by high energy-to-power ratio, thus capacity expressed in energy terms (Figure 6 lower figure) is shown to represent more than one-third of global electrochemical capacity in 2017.

Source: JRC based on US DOE [56]. *Note*: including only grid-connected energy storage; the reported power (kW) and storage duration were used to calculate the total installed capacity of the projects in GWh.

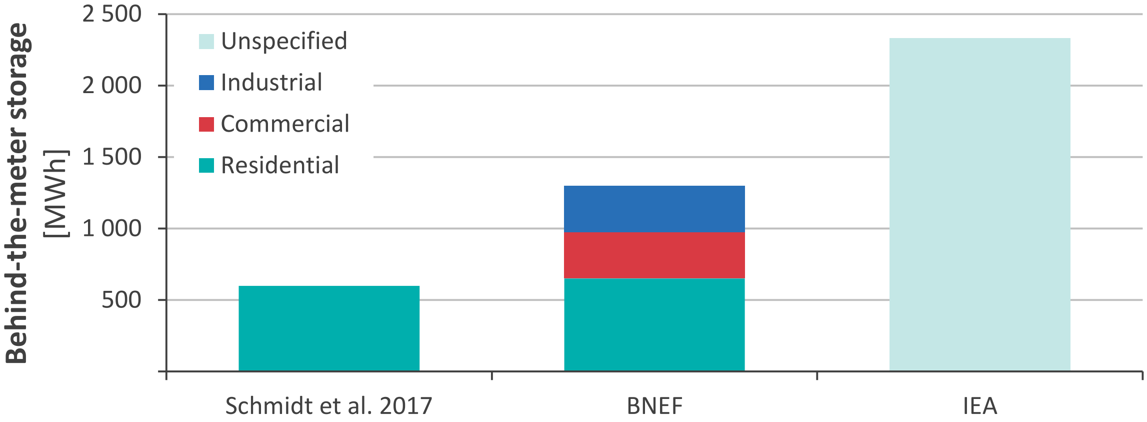
Deployment of residential Li-ion batteries behind-the-meter, was estimated at around 600 – 650 MWh (or about 200 MW) in 2016 [57,58], which is not negligible considering that it represents almost 20 % of the total Li-ion battery capacity installed for system storage. BNEF reports additional behind-the-meter storage capacity of 650 MWh in commercial and industrial sectors [58]. Other sources estimate that global installed capacity of behind-the-meter storage was 2 300 MWh, without, however, specifying the battery type or the sectoral application [59] (Figure 8).

Figure 7 Global annual sales of electrochemical storage



Source: JRC based on US DOE [56].

Figure 8 Global installed capacity of energy storage installed behind-the-meter in 2016



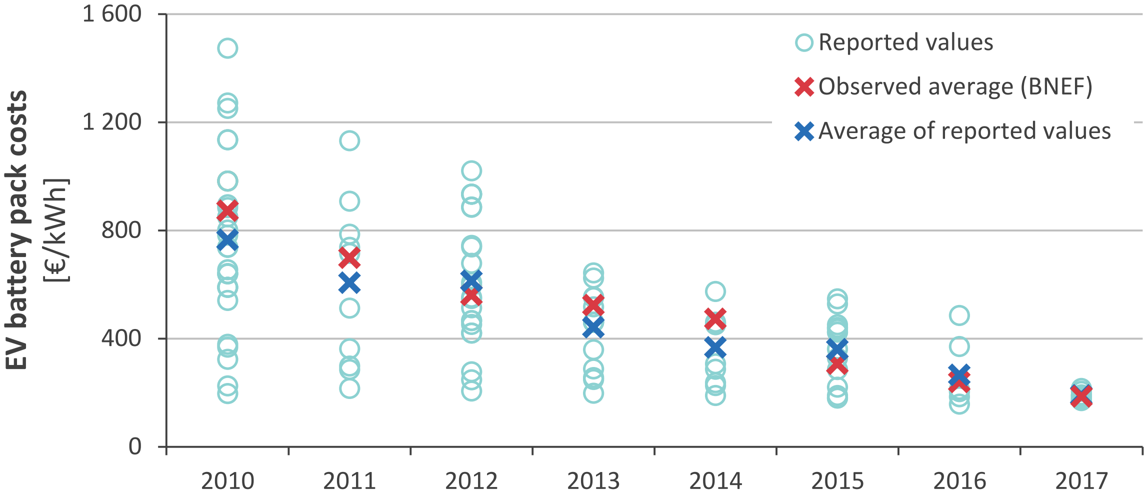
Source: JRC based on different literature sources [57–59].

2.2 Li-ion battery costs and cost structure

2.2.1 EV battery pack costs

One of the most widely cited overviews of EV battery pack costs is provided by Nykvist and Nilsson [60], which is summarised and complemented with recent data in Figure 9. The figure reveals a wide variation of reported historical costs, which on average range about ± 60 % from observed values reported by market analysts ([9]). Observed costs of EV battery packs based on BNEF have decreased from about 870 €/kWh in 2010 to 170 – 215 €/kWh in 2017 (Figure 9) [26]. The range or reported values from the observed values of BNEF (190 €/kWh in 2017) is about ± 15 % in 2017. The lower end of the cost range of 2017 coincides with announcements of market leaders, like Tesla, at about 170 €/kWh [61].

Figure 9 Reported Li-ion battery pack costs for EVs



Source: JRC based on Nykvist and Nilsson [60], IEA's World Energy Outlook [62,63], IEA's Global EV Outlook [45], SET Plan [23], Boston Consulting Group [64], IDTechEx [52], Deutsche Bank [65] and Avicenne Energy [66]. *Note*: Observed average prices are based on BNEF's industry survey and are a volume-weighted average of Li-ion battery pack prices for EVs [26,67]. Reported average is the simple average of the data included in the graph.

One reason for the spread is that announcements made by market leaders were typically lower than what the industry reported [60]. Reported metrics are not always consistent across the different sources, as these may represent either production costs or market prices of battery packs. For example, the difference between these two metrics was found to be about 15 % in 2015 [68]. Data published by Avicenne Energy shows low profitability or operation at loss of Li-ion cell manufacturing business with Earnings Before Interest & Tax (EBIT) in 2016 of market leaders such as Panasonic, LG Chem and Samsung SDI being 0 %, -1 % and -13 % [47]. Large size and multi-sectoral business structures may enable some battery manufacturers to offer their products at a very competitive price and to absorb large financial losses caused, for example, by product recall (e.g. the recall of Galaxy Note 7 due to the safety issues with its battery costed Samsung 5.3 bn $ [69]). A factor that works in the opposite direction, i.e. towards price increase, is illegal price fixing. Several Li-ion cell manufacturers, including Samsung, LG Chem, Sony, Sanyo, Panasonic, NEC, Toshiba and Hitachi, have been accused of a long-term antitrust violating price-fixing conspiracy that kept prices for cylindrical Li-ion batteries artificially high from 2000 to 2011 [70]. While settlements have been reached with Sony, LG Chem, NEC and Hitachi, the case is continuing against the remaining Non-Settling Defendants. The above reported factors and practices underline the important difference between the terms “price” and “cost” in the context of the global Li-ion sector and offer additional insights into the reasons behind widely varying numbers reported.

([9]) Compared with the volume weighted average of BNEF's price survey [26].

Different battery sizes could offer another explanation, as large batteries tend to have lower specific costs [45] ([10]). Battery chemistries ([11]) (Table 1, Figure 10), cell quality, or cell size and format also affect the cost of a battery pack, with a 18650 cylindrical cell being about 30 % cheaper than a large prismatic EV cell [45,47]. The material requirement of different cathode chemistries is shown in Figure 11 ([12]). Nickel-Manganese-Cobalt oxide (NMC-111) cathodes are one of the main types used in EV batteries (e.g. by Nissan Leaf, BMW i3, GM Chevrolet Bolt [71]). Besides the EV market, behind-the-meter storage applications, such as Tesla's Powerwall, also use cells with NMC cathodes [72,73]. NMC and Lithium-Iron-Phosphate (LFP) batteries seem to be the mainstream choice for storage applications from 2017 onward [74]. The industry aims at reducing cobalt demand in cathodes by developing and bringing into the market nickel-rich NMC-811 cathodes (e.g. LG Chem, BYD, SK innovation [74–76]). This may reduce supply risks on critical materials and improve battery pack costs and performance (e.g. capacity, energy density) [71,77–79]. Some experts and analysts see a wide adoption of NMC-811 cathodes in the EV market after 2025 [66,77], while others expect it to become the primary choice by the early 2020s [26] (Figure 12). The second type of cathodes with widespread commercial use is Nickel-Cobalt-Aluminum oxide (NCA) mainly produced by Panasonic for Tesla EVs [80]. These cathodes use about 65 % less cobalt than NMC-111, which could at least partially explain the difference between Tesla's announcements and other manufacturers on reported costs [72].

Table 1 Main cathode chemistries used in Li-ion battery packs and their application

Main cathode chemistries	Main application
Nickel Manganese Cobalt oxide (NMC)	EVs, storage, other (e-bikes, medical devises, industrial)
Nickel Cobalt Aluminum oxide (NCA)	EVs, storage, other (medical devices, industrial)
Lithium Cobalt Oxide (LCO)	Portable electronics
Lithium Manganese Oxide (LMO)	Power tools, medical devices
Lithium Iron Phosphate (LFP)	EVs, electric buses, storage

Based on the weighted average of the global EV car fleet on the road between 2011 and 2017, NMC batteries represent 53 % of the market, NCA batteries 46 % and the remainder are LFP or other chemistries ([13]). The predominant battery chemistry for electric buses is LFP and their main market is in China (and to a lesser extent NMC cathodes) [49]. In 2018, 88 % of the battery chemistries used in electric buses were LFP [49]. By 2028, it is expected that NMC batteries will gain market share in this segment (42 % NMC and 58 % LFP chemistries [49]).

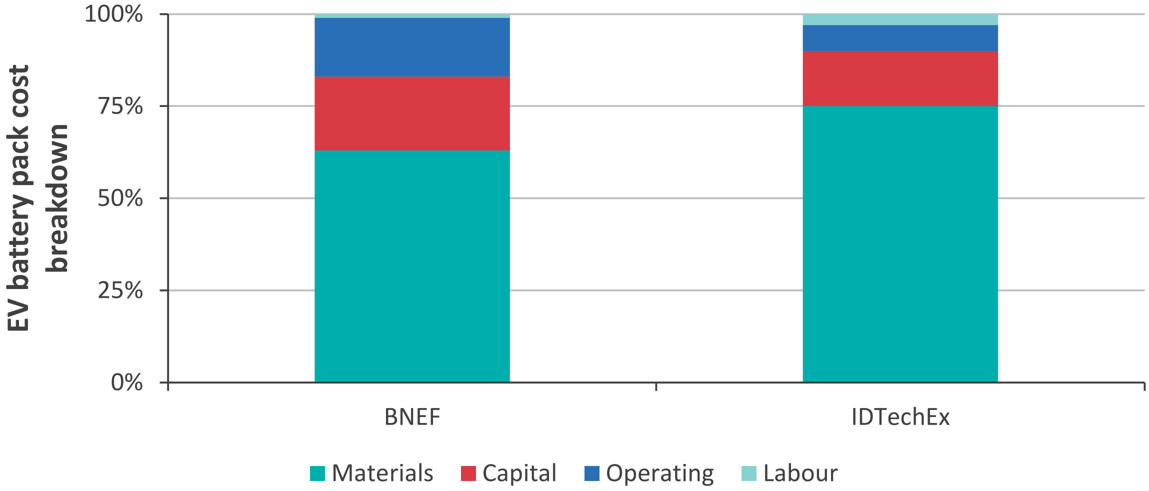
([10]) IEA mentions that a 70 kWh battery is expected to have a 25 % lower cost per unit of energy stored than a 30 kWh battery, due to the higher cell-to-pack ratio of the former [45].

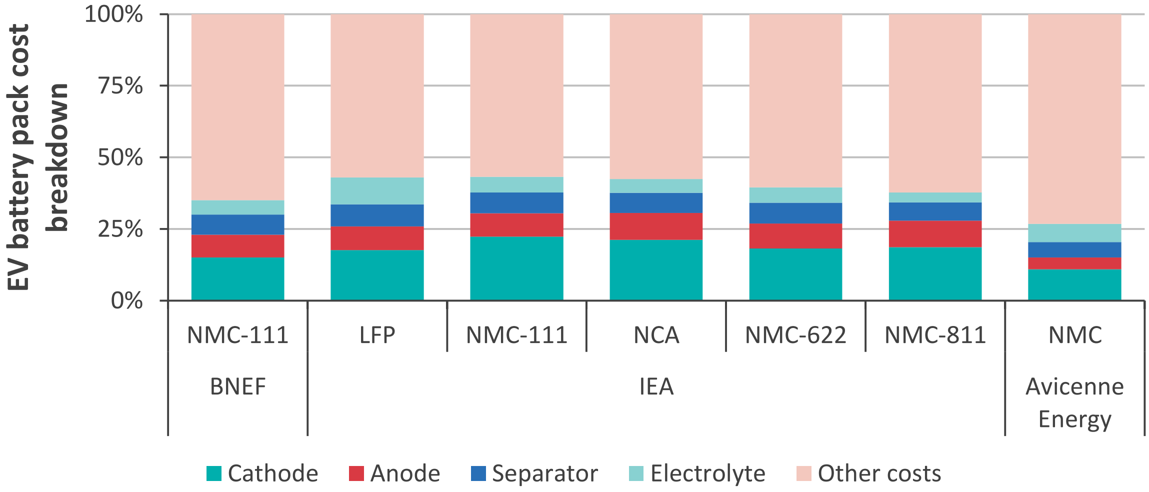
([11]) Based on IEA, the cost of a NMC-111 battery is about 5 % higher than the cost of an NCA battery [45].

([12]) When taking into account the process yield of the battery (by cell format and application), the actual material consumption is higher than the element composition shown in Figure 11. Based on Avicenne Energy, the cobalt needs for NMC-111 were 0.49 kg/kWh in 2015 decreasing to 0.41 kg/kWh by 2025, and for NCA from 0.22 kg/kWh to 0.18 kg/kWh over the same period [66]. Back of the envelope estimates from other sources and for unspecified cathode chemistry, indicate much higher range for cobalt use from 0.36 up to 1.44 kg/kWh [78].

([13]) This estimate excludes China, which historically has been relying mainly on LFP batteries and is now gradually shifting to NMC batteries [127,128].

Figure 10 Breakdown of the total cost of Li-ion EV battery in key components (upper figure) and between cell components and other costs across different chemistries (lower figure)





Source: JRC based on BNEF, IDTechEx (upper figure; [26,52]) and BNEF, IEA and Avicenne Energy (lower figure; [26,45,66]).

Based on the average of raw material prices over the last 8 years, the majority of the materials for the cell and pack of NMC-111 batteries cost about 37 €/kWh, with cobalt and copper representing about two-thirds of that cost. The majority of the materials in NMC-811 batteries cost about 30 €/kWh, with copper and nickel covering almost 70 % of the cost. In the case of NMC-811, lithium and cobalt each represent about 10 % of the total material costs (see assumptions in Annex 2) ([14]).

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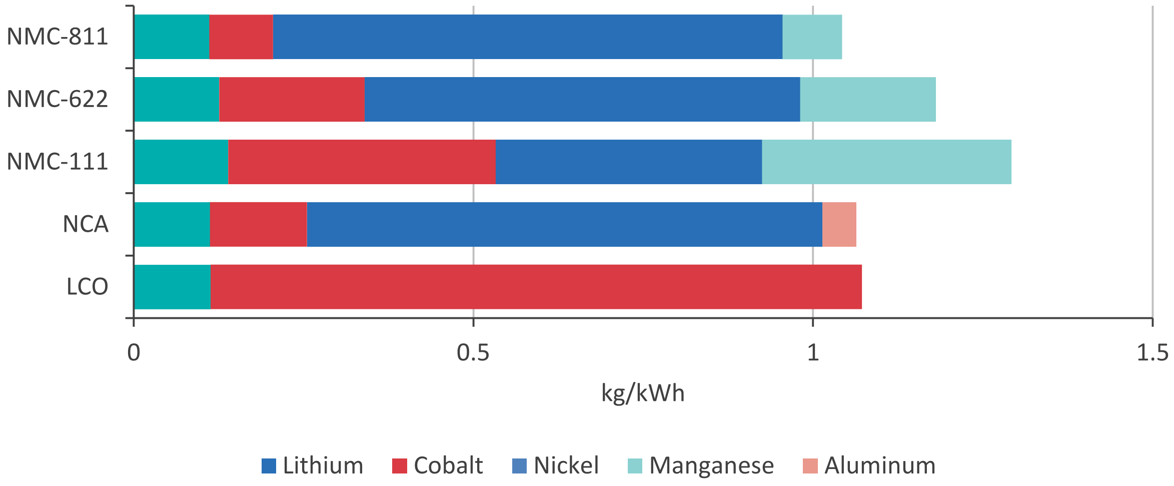
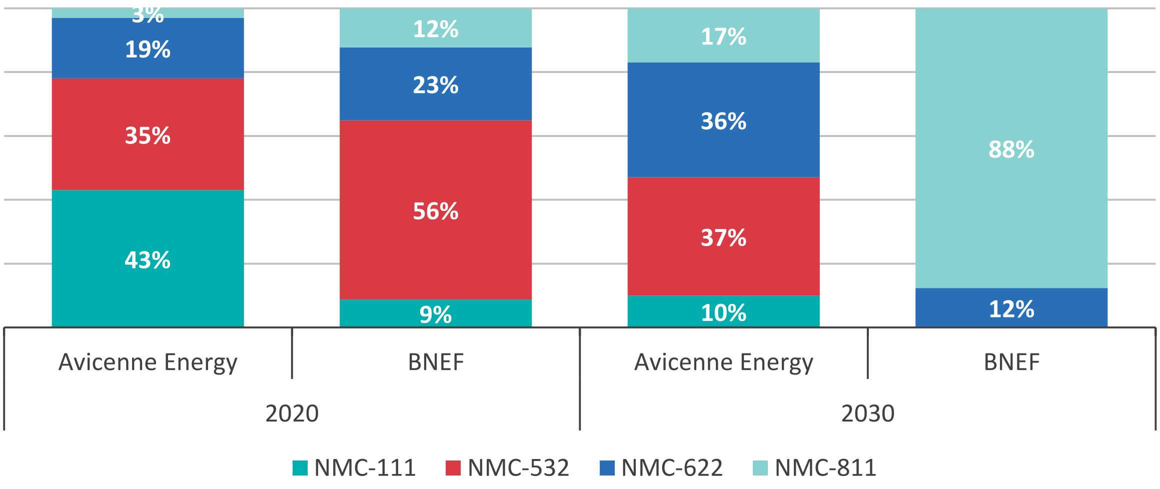
[14] Based on historically high prices of raw materials of the last 8 years, NMC-111 material costs are estimated at about 80 €/kWh and NMC-811 are estimated at 50 €/kWh.

Figure 11 Element requirement for Li-ion battery cathodes



Source: JRC based on Olivetti et al. [77].

Figure 12 Future NMC chemistry mix in cathodes



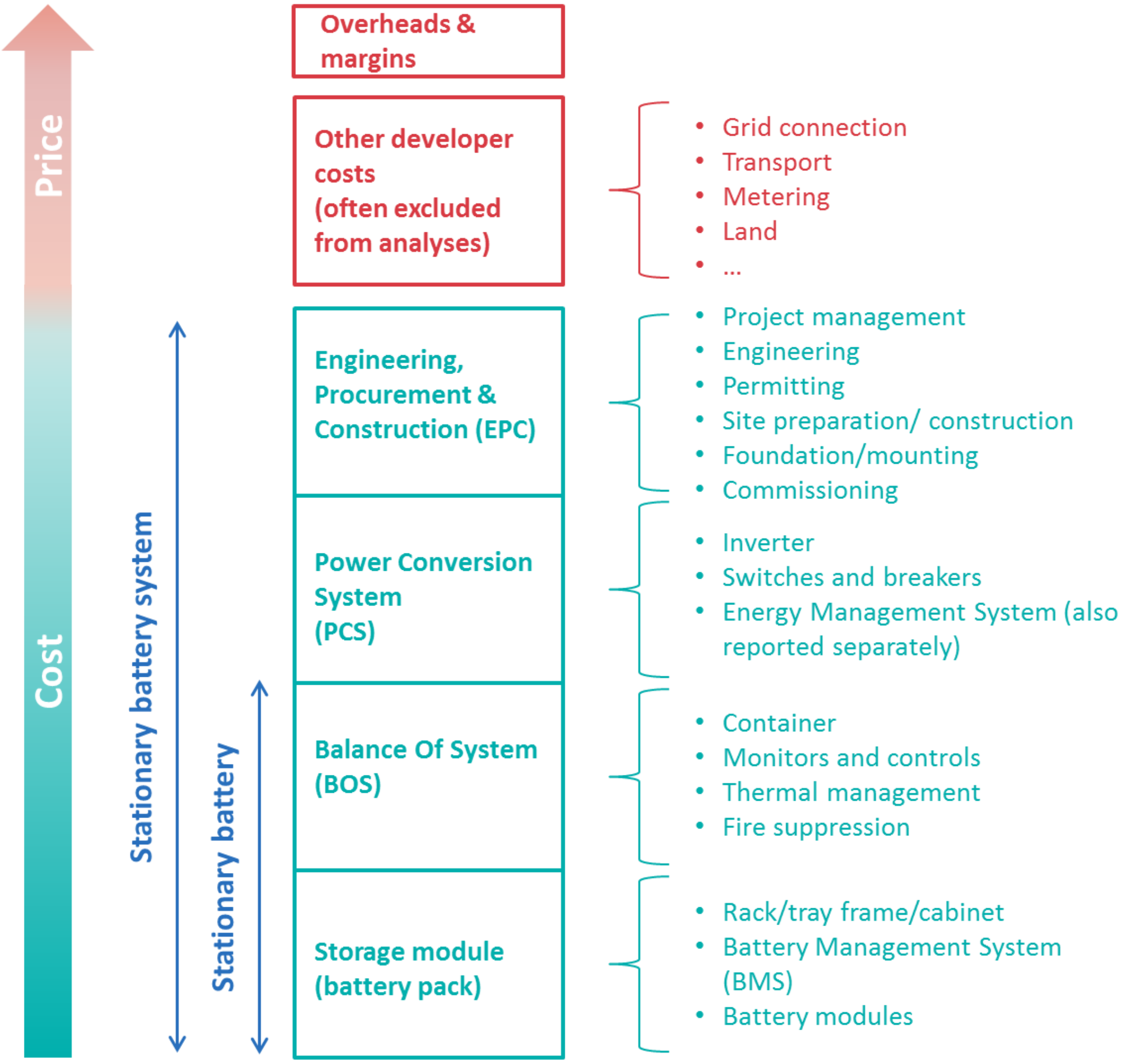
Source: JRC based on different experts and analysts [26,81].

2.2.2 Stationary battery system storage costs

Li-ion battery system costs for stationary storage have been witnessing a downward trend, from 1 800 – 1 900 €/kWh in 2010 to 1 100 – 1 700 €/kWh in 2015 [57,65]. In 2017, the reported figures average at much lower costs at around 570 €/kWh, due to the dive of battery pack prices and balance of system costs (BOS) [82]. Factors such as boundaries (e.g. grid connection; see Figure 13), application (e.g. utility, behind-the-meter), type of service (e.g. peak replacement, frequency control), size (e.g. kW, MW), chemistry (e.g. NMC, LFP) characterise the technology and its costs. These vary across the different studies and are not always reported, which could explain the wide spread, shown in Figure 14. For example, IRENA mentions that already in 2016, under optimal conditions, energy installation costs of Li-ion batteries for stationary storage may be as low as 220 €/kWh, comparable with EV battery packs (section 2.2.1), possibly because they include only electrochemical and power electronic components in the technology boundaries. This estimate is almost a factor 10 lower than the approximately 1 400 €/kWh required for a behind-the-meter system based on Schmidt et al. [57]. As such, a direct comparison of Li-ion battery stationary storage system based on multiple sources on system costs or more detailed cost structures is not always feasible.

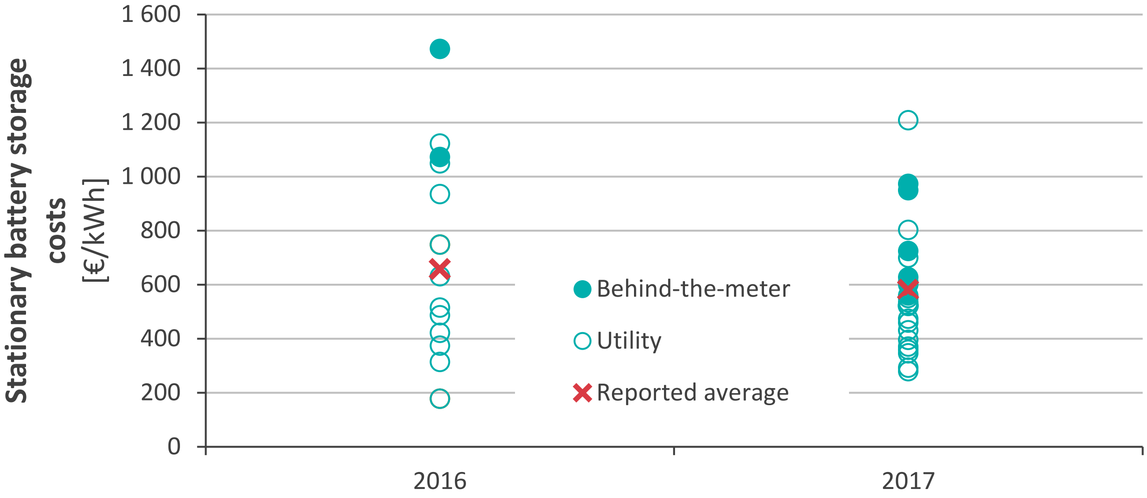
Costs of other battery types suitable for stationary storage systems range between 100 and 400 €/kWh for lead acid technologies at utility scale [4,83] and 1 250 €/kWh at residential scale [57], between 220 and 640 €/kWh for sodium-sulphur batteries [4,83], and from 450 to 1 450 €/kWh for zinc-bromide flow batteries [83].

Figure 13 Illustrative system cost and price structure of stationary battery storage



Source: JRC based on Lazard and BNEF [84,85].

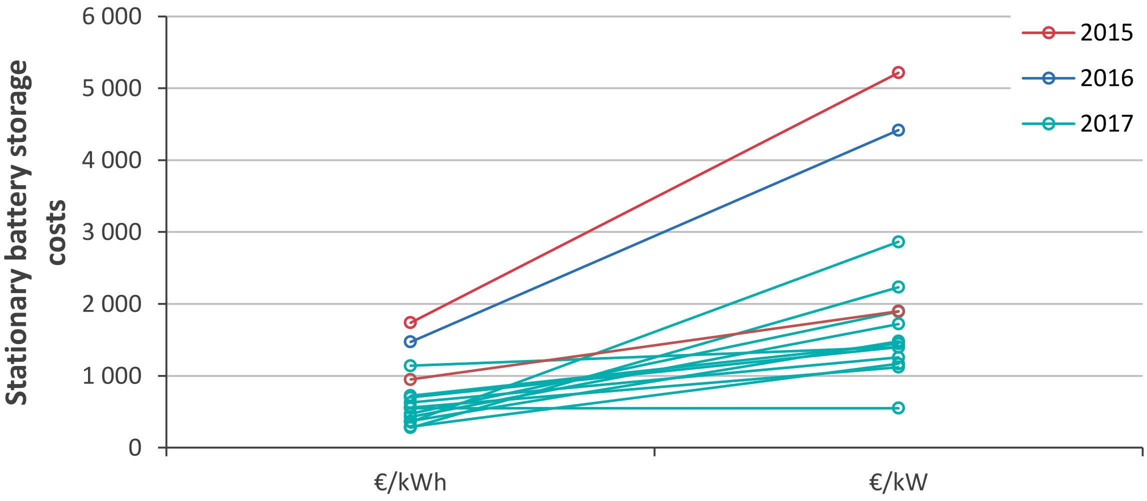
Figure 14 Li-ion battery stationary system costs in 2016 and 2017



Source: JRC based on Schmidt et al. [57], BNEF [85], IRENA [83], IEA [63], Deutsche Bank [65], Lazard [84] McKinsey [86] and Navigant [87].

Another aspect to consider is that Li-ion batteries may be used to cover a range of services in the power sector. The battery configuration (power output and energy capacity ratio) depends on the system requirements and the desired service. Specific costs expressed per unit of power range from being similar to a factor 8 higher when compared with specific costs expressed per unit of energy (Figure 15). Moreover, the spread of reported costs widens when expressed per unit of power compared with costs expressed per unit of energy (Figure 15).

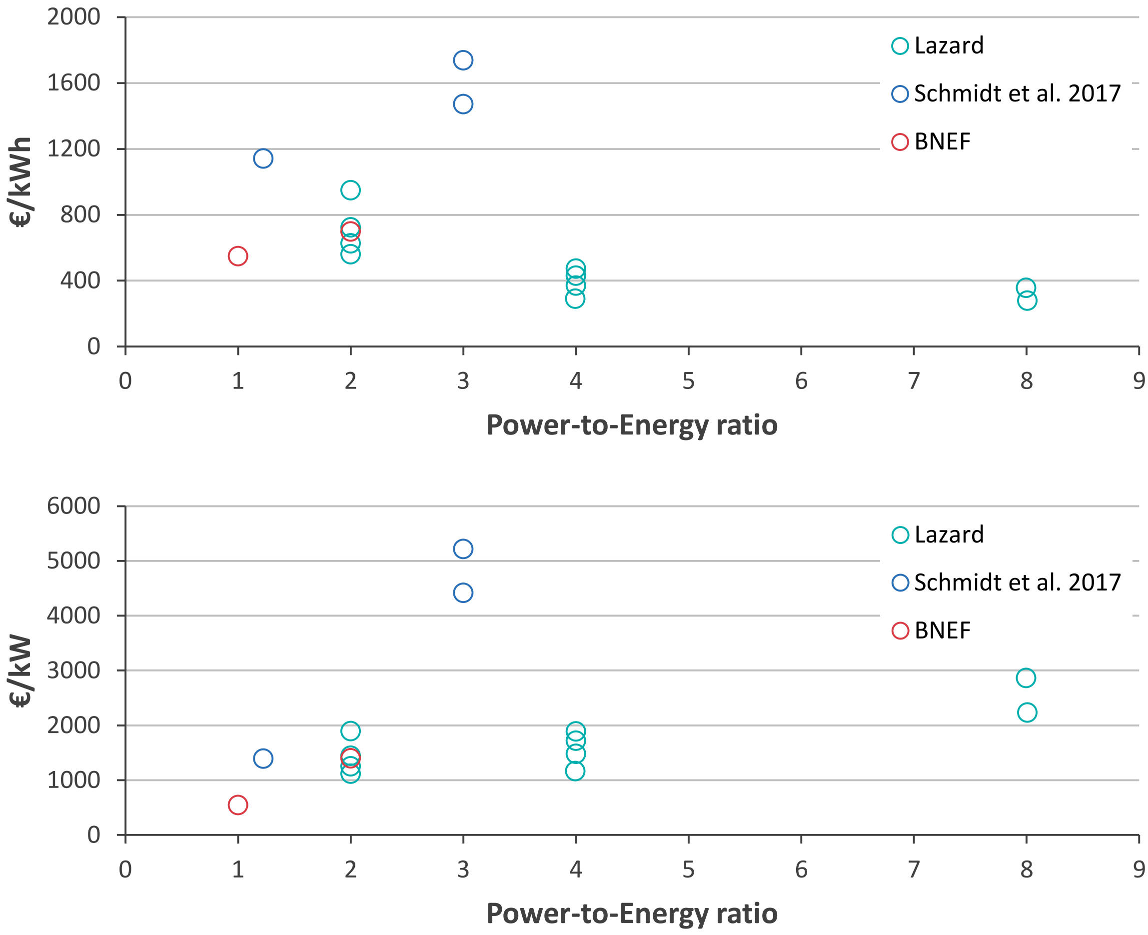
Figure 15 Specific costs of Li-ion battery for stationary system storage expressed per kW and kWh



Source: JRC based on Schmidt et al. [57], BNEF [85] and Lazard [84].

Batteries for stationary storage are used for a range of applications with some being more suited to store energy and others to supply power. It is observed that with increasing power-to-energy ratio the specific costs tend to decline when expressed per unit of energy and tend to increase when expressed per unit of power (Figure 16). Generally, it is preferable to express specific costs of battery systems tailored to deliver energy for a long period of time (energy-designed system) per kWh and for a system tailored to deliver more power but for a less amount of time (power-designed system) per kW [85]. In the present report, batteries that can provide energy for more than 1 hour are called energy-designed and batteries that can provide energy for less than 1 hour are called *power-designed.* Smaller scale residential batteries provide energy for more than 1 hour and do not require system integration components.

Figure 16 Specific system costs of Li-ion battery for stationary storage expressed per kWh (upper figure) and kW (lower figure) and power-to-energy ratio



Source: JRC based on Schmidt et al. [57], BNEF [88] and Lazard [84].

The distribution of power-to-energy ratios of projects with similar size is comparable across different databases (Figure 17). *Utility-scale projects* tend to be more energy-designed (power-to-energy ratio lower than 1), whilst commercial- or residential-scale projects tend to be power-designed (power-to-energy ratio > 1). The spread of values in Figure 17 indicates that the design of the system is project specific.

The cost structure of battery storage systems in 2017 is shown in Figure 18. Regardless of the system service, the battery pack is a key cost component that represents 42 to 50 % of the total cost (15). The Power Conversion System (PCS), comprised mainly by the inverter, is a major cost component in power-designed storage systems, while in energy-designed storage systems the Energy Management System (EMS) becomes more important (a description of the cost components of stationary battery storage systems is presented in Figure 13).

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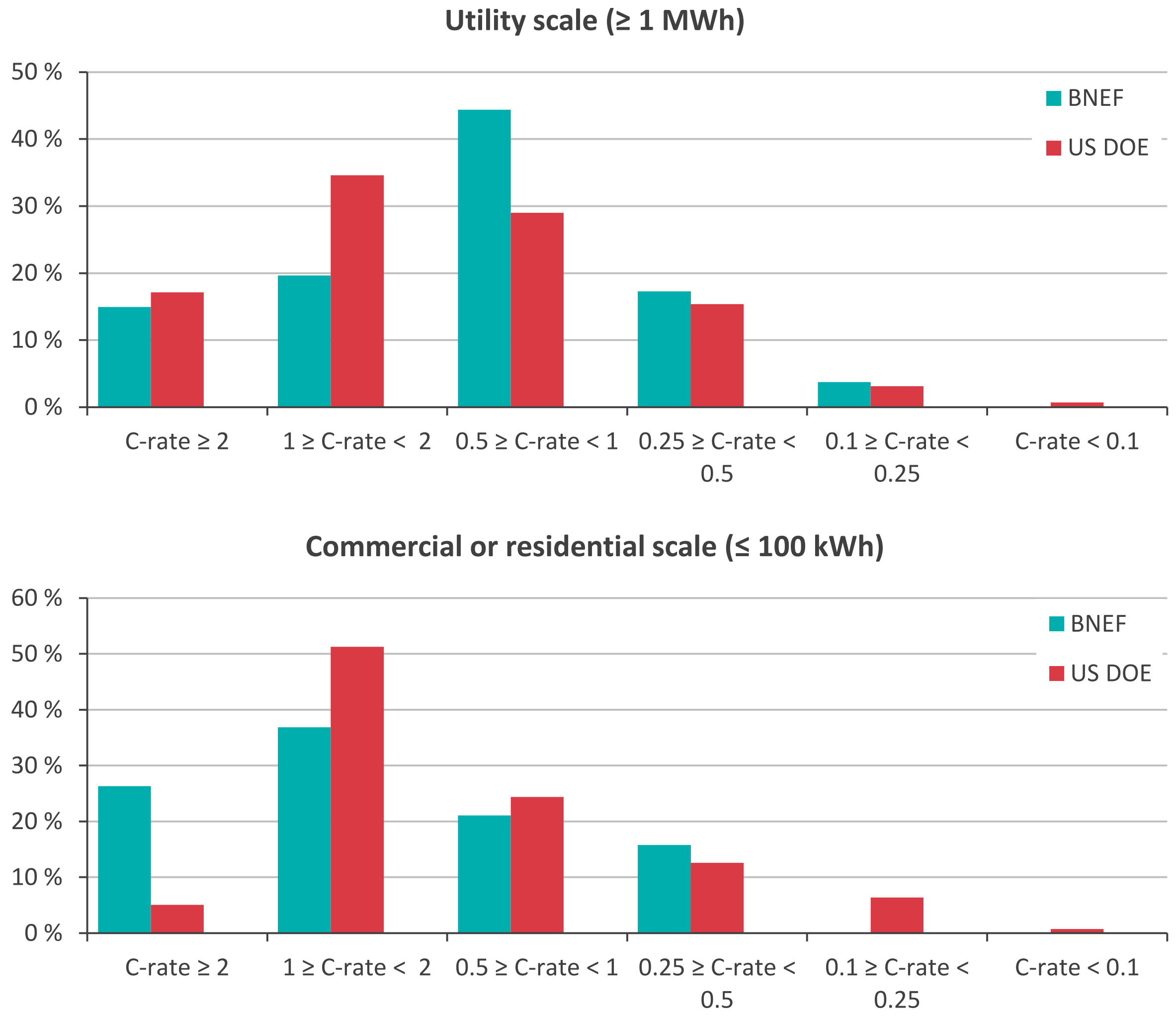
(15) The cost of battery packs for EV and stationary storage applications are similar. However, different requirements between applications (e.g. technical, long term functionality and external constraints [119]) could partially explain differences at a pack or at a systems level.

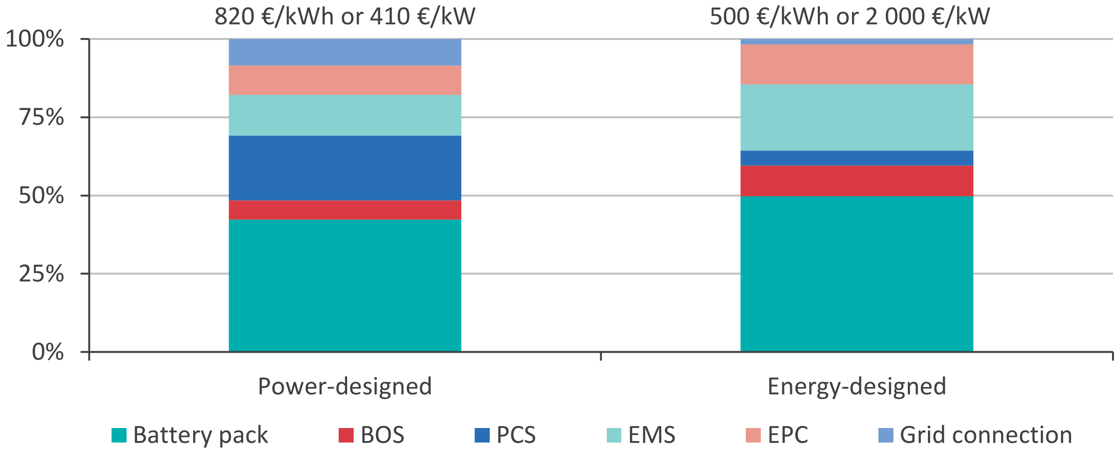
Figure 17 Distribution of power-to-energy ratio based on project size



Source: JRC based on BNEF [88] (214 projects > 1 MWh, 19 projects < 100 kWh) and US DOE [56] (136 projects > 1 MWh, 119 projects < 100 kWh). Residential applications are not included in the datasets. *Note*: Lazard's industry survey data [84], indicate for utility-scale projects (4 to 400 MWh) a ratio between 0.15 and 0.25 (energy-designed systems). For commercial or residential applications (10 to 250 kWh), Lazard's reported ratio is 0.5 (energy-designed). *Note*: The discharge rate of a battery is expressed by its C-rate. The capacity of a battery rated at 1C means that a fully charged battery will be completely discharged in 1 hour. 2C rate means that the battery can be fully discharged in half an hour. ½C rate means that the battery can be fully discharged in 2 hours.

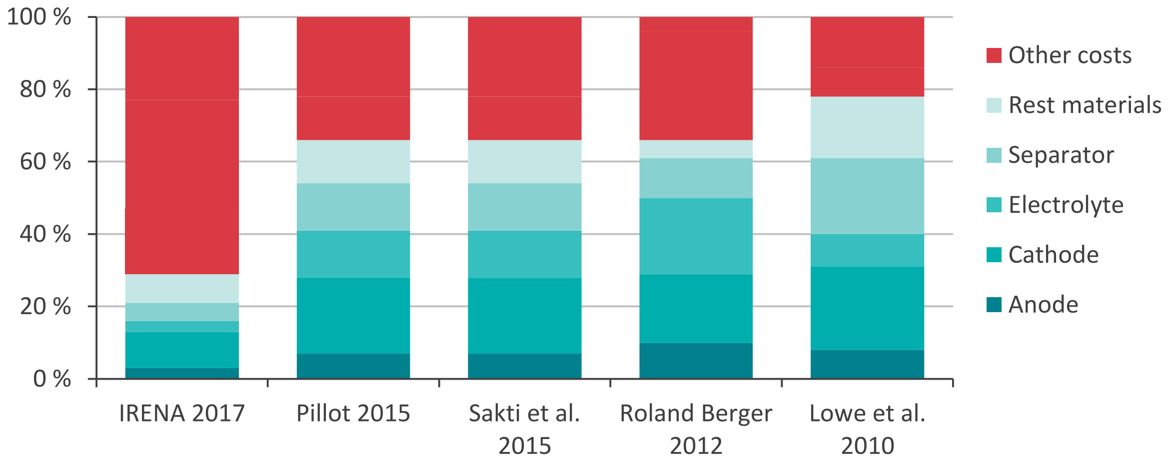
According to most studies, the division of Li-ion battery storage systems into components (Figure 19) shows that materials contribute 65 to 80 % (similar with the contribution of materials in EV battery packs; section 2.2.1) and the remainder is mainly labour, overhead, margins and other non-material costs. IRENA estimates the cost contribution of materials to be less, at 30 % of which two-thirds are cell costs, and attributes the remainder to other system costs [83]. The disparity in the cost-structure between the sources is possibly due to different system boundaries (IRENA assesses stationary system storage, while the other sources assess battery packs).

Figure 18 Cost breakdown of power-designed (C-rate 2) and energy-designed (C-rate 0.25) grid-scale stationary storage system



Source: JRC based on average costs in BNEF's survey [85]. *Note*: Balance of System (BOS), Power Conversion System (PCS), Energy Management System (EMS), Engineering, Procurement and Construction (EPC).

Figure 19 Cost breakdown of Li-ion battery storage system between cell components and other costs

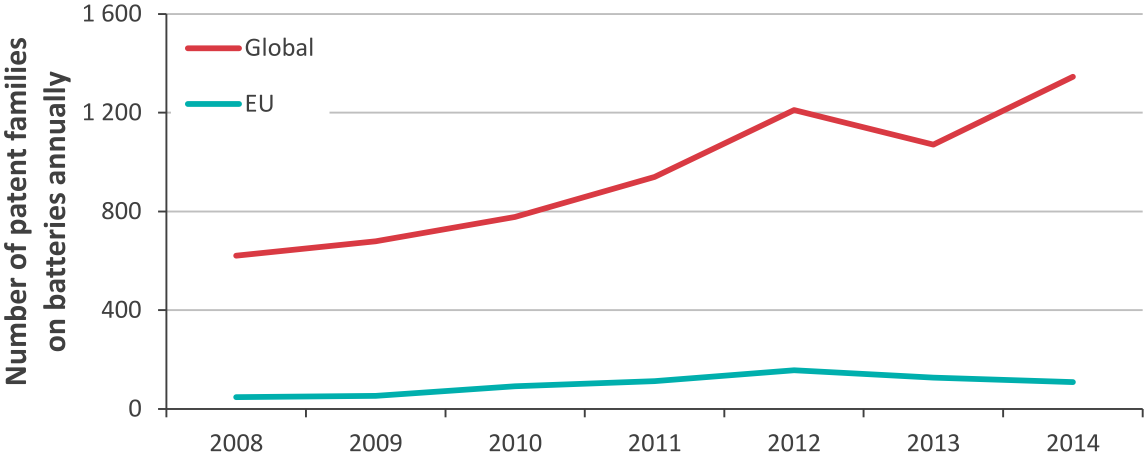


Source: IRENA and sources therein [83]. *Note*: sources in IRENA [83] represent cost breakdown of Li-ion battery packs.

2.2.3 Cost reduction drivers

The fast growing pace of EV sales over the last years and the slower growth of other Li-ion battery markets (Figure 1) have led to volume-driven cost reduction, owing to technical progress (e.g. battery chemistries), improvements in manufacturing and economies of scale. The growing research and innovation activity as measured by patent statistics (Figure 20) may have also been contributing at an accelerating rate. Kittner et al. [89] estimate a reduction in the order of 2 % per 100 patents (Patent Cooperation Treaty; PCT), while the rest may be attributed to increasing production scale. Beyond technical factors, the U.S. Department of Energy identifies three reasons that can explain the price drop, based on market conditions and business strategy [68]. These are: production overcapacity that may lead to supply-demand imbalances, competitive long-term supply contract offerings that are based on anticipated cost reduction and finally, strategic corporate behaviour.

Figure 20 Annual patent activity on batteries filed globally and by the EU



Source: JRC method [90] based on PatStat data (Autumn 2017 edition). *Note*: Global numbers include the EU.

The expected market surge, primarily of EVs [91], entails growth in production and manufacturing scales, in view of the announced megafactory and gigafactory capacities around the world (section 3.1). This may act as a driver for further cost reduction due to economies in production scale. Accumulated experience may also lead to improved and optimised manufacturing processes, bringing the costs of Li-ion further down. Moreover, by means of vertical integration of production steps across the value chain (e.g. cell and pack production), transportation expenses and turnaround time could decrease leading to lower costs [43].

In addition, whilst several chemistries of Li-ion batteries already exist in the market (e.g. NMC, NCA, LFP, LCO [92]), there are continuous efforts on improving Li-ion battery cathode chemistry and material composition aiming to deliver better performance (e.g. higher energy density), lower specific costs and removing other bottlenecks such as the dependence on cobalt. It is not known which the dominating cathode chemistry will be or when it will emerge at commercial scale as different expectations are expressed by analysts (Figure 12).

Ongoing research on further improving Li-ion battery chemistries (e.g. high-voltage electrolytes, durable lithium manganese oxide cells), combining conversion cathodes with silicon-containing anodes, or moving beyond Li-ion (e.g. lithium-metal, solid state, lithium-sulphur, lithium-air) signals to greater cost reduction potential [36,78,83]. Forecasted battery technology evolution, originally presented by the German National Platform for Electromobility [93] and adopted in the preceding JRC publications on key issues related to Li-ion batteries [36,43], gives an indication of the timeline for the commercialisation of future battery technologies for mobility applications. The situation is less clear with technologies for energy storage because of the large diversity of services.

Finally, the multiple applications in which Li-ion batteries are used, may offer additional synergies for learning. Stationary storage system costs may benefit from large photovoltaic inverter manufacturers entering the market thus reducing PCS costs. Scale effects based on project size could affect other components such as BOS and Engineering, Procurement and Construction (EPC), as well as standardisation of system design, design improvements, engineering and competitive markets [82,86].

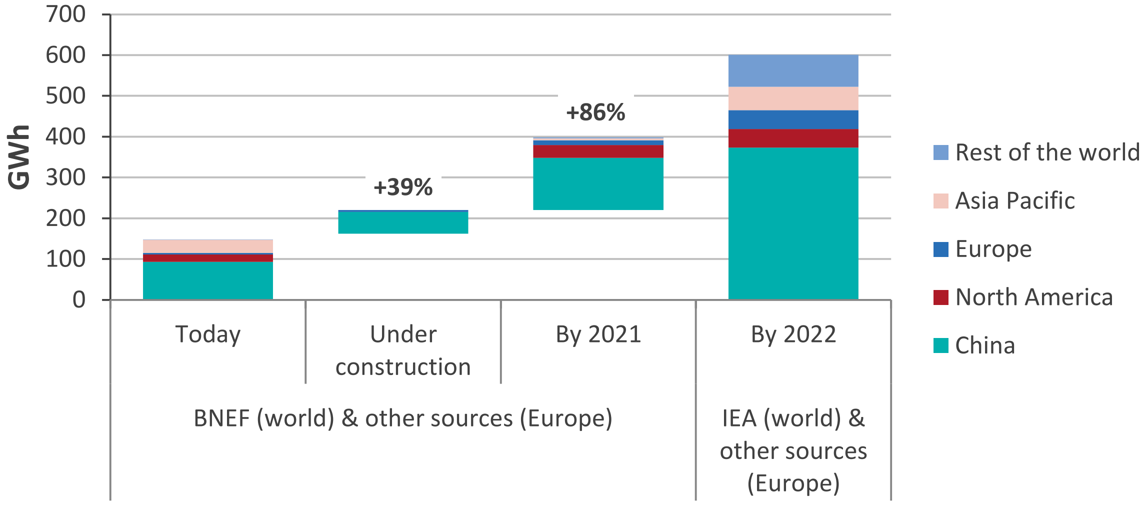
3 Future growth and costs of Li-ion batteries

3.1 Market growth of Li-ion batteries

3.1.1 Near-term manufacturing capacity growth globally and in the EU

Global manufacturing capacity of Li-ion cells for EVs and stationary storage is around 150 GWh, with two-thirds of the capacity being located in China [94]. In recent years, production was characterised by low utilisation rates of about 50 % [66] and overcapacity. Based on company announcements, substantial growth is expected in the near future, ranging from additional 240 to 450 GWh [59,94,95]. That is, by 2022, global Li-ion cell production capacity will be 2.5 to 4 times higher than today. With both EV sales and the global manufacturing capacity for Li-ion battery cells rapidly increasing, the market situation is expected to come into better balance in the near future [36]. Noticeable is that while the future market share of Li-ion cell manufacturing belongs to Asian players (Figure 21), steepest growth is expected in Europe, owing to the limited domestic capacity today. By 2022, the global share of European Li-ion battery cell manufacturing capacity is expected to increase from about 3 % today to 8 % (Figure 21). By 2028, due to additional capacity and plant expansions in Europe total Li-ion cell manufacturing capacity may reach about 105 GWh, if all current plans and announcements materialise. In the coming decade, depending on the year that the new production lines become operational and near-term market projections, Europe may serve between 7 and 25 % of global demand (Table 2, Figure 24). Most of the capacity will be located in Sweden, Germany and Poland (Table 2, Figure 22).

Figure 21 Expected near-term growth in global Li-ion cell manufacturing capacity for applications such as EVs and stationary storage



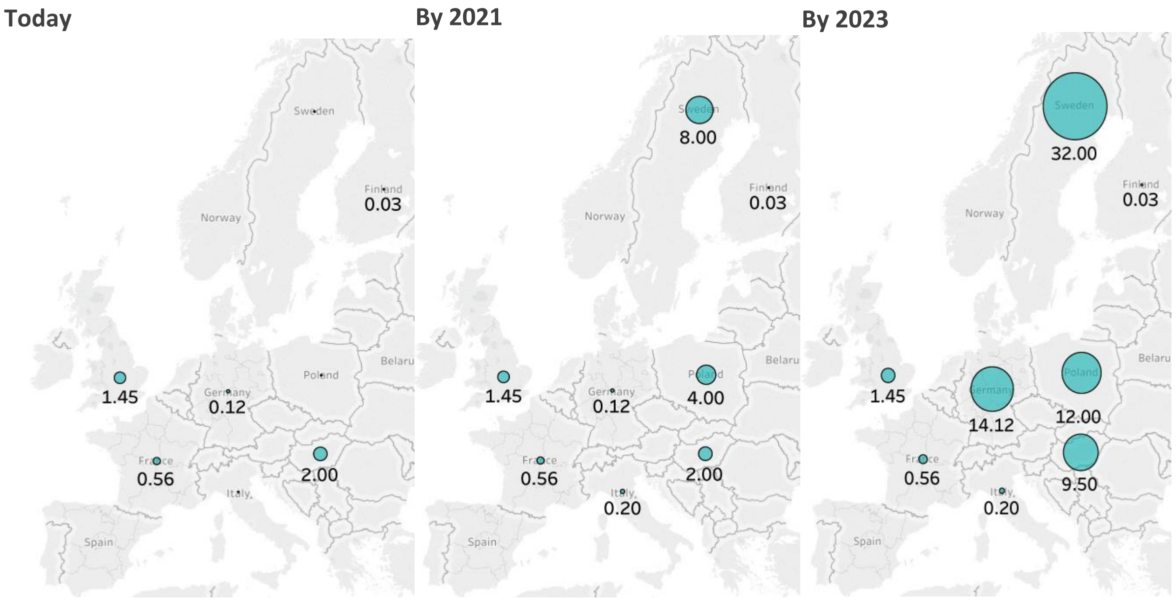
Source: JRC based on BNEF [94] (world) and other sources for Europe [36,95–97]. IEA data used for 2022 [59].

Table 2 Producers of Li-ion cells for mobility and stationary storage applications in the EU (including the UK) today and in the near term [36,94–98] (1)

Manufacturing	Company name	Capacity, GWh	Headquarters
Currently operating facilities			
Hungary	Samsung SDI Co Ltd	2	South Korea
UK	Nissan	1.4-1.5	Japan (2)
France	Bollore SA	0.5	France
Germany	Leclanche GmbH	0.1	Switzerland
France	SAFT	0.06 (3)	France
Finland	European Batteries Oy	0.03	Finland
Germany	Custom Cells	0.02	Germany
Facilities under construction, expected to begin production by 2021			
Poland	LG Chem Ltd	4 (2019), up to 9-12	South Korea
Italy	SERI (FAAM)	0.2 (2019)	Italy
Announced facilities, expected to begin production after 2021			
Sweden	NorthVolt AB	8 (2020), 32 (2023)	Sweden
Hungary	SK Innovation	7.5 (2022)	South Korea
Germany	CATL	14 (2022)	China
~~Germany~~	~~TerraE~~ (4)	~~0.9 (initially), 34 (2028)~~	~~Germany~~

(1) Between 2020 – 2028, other announcements include a 35 GWh plant by Tesla at undisclosed location [95]. In addition, according to Reuters, SAFT (FR) and partners plan to produce advanced Li-ion batteries in the EU from 2020 [97], Varta Microbattery Systems (DE) and Ford plan to establish Li-ion battery cell production in Germany [99] and BYD (CN) at undisclosed location in Europe [100]. (2) Nissan entered into a definitive agreement with Envision Group (headquarters in China) for the sale of Nissan's battery operation and production facilities. The deal, pending regulatory approvals, is expected to be completed by March 29, 2019 [101]. (3) Data on the exact manufacturing capacity of SAFT in France for cells for stationary energy storage application is unavailable; hence full manufacturing capacity of SAFT is France is cited based on data from Lebedeva et al. [36]. (4) The dissolution of the TerraE consortium has been announced in October 2018 [102].

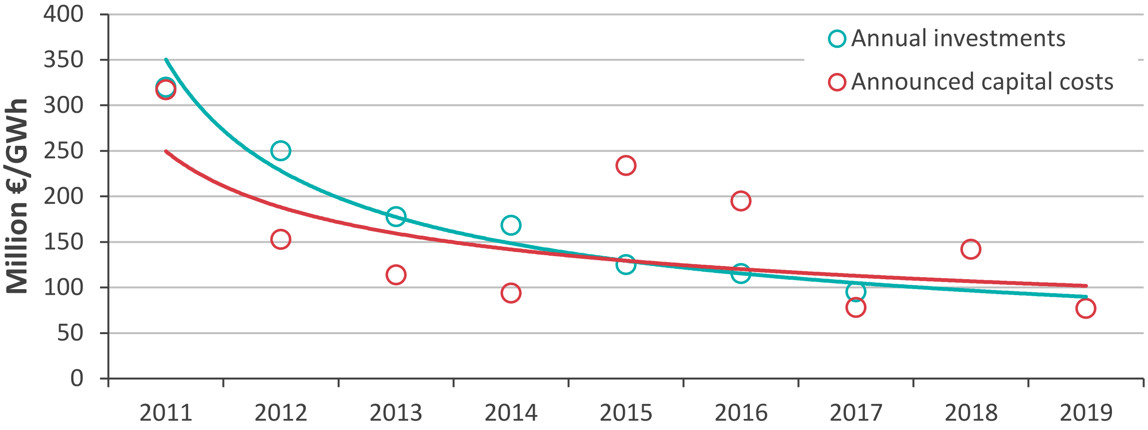
Figure 22 Expected evolution of Li-ion cell manufacturing capacity for mobility and stationary storage applications in the EU (incl. the UK), in GWh



Source: JRC based on various sources [36,94–98]. *Note*: Excluding the announcement made by TESLA as the location was not disclosed.

Figure 23 summarises the development of specific annual investments of capacity added and announced battery plant costs based on IEA [59]. While some difference is noticed between announced capital costs and investments, the trends converge to about 100 million €/GWh in 2017, or 70 % lower compared with the beginning of the decade ([16]).

Figure 23 Annual investments in new Li-ion cell manufacturing capacity and announced capital costs per unit of battery manufacturing capacity

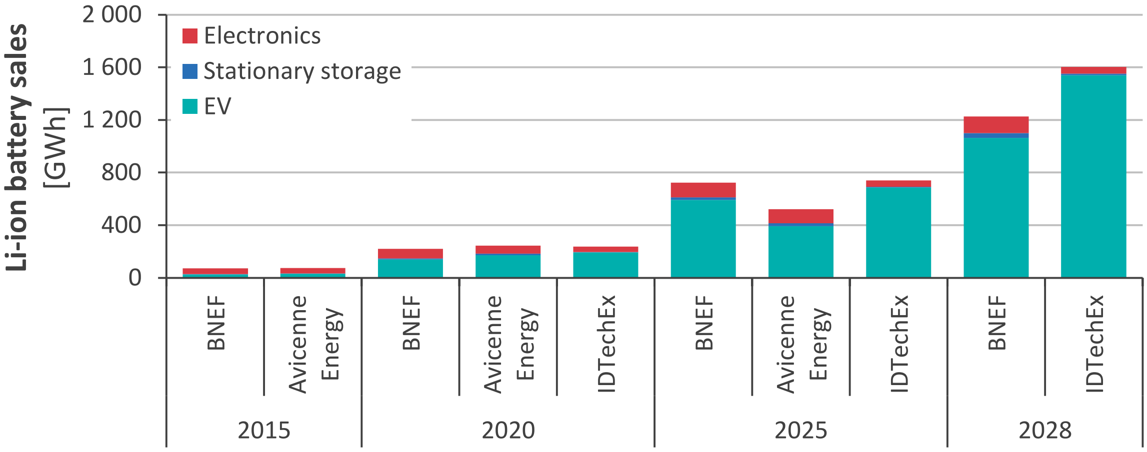


Source: JRC based on IEA [59].

3.1.2 Global long-term manufacturing capacity growth

Globally and in the longer term (towards 2040), annual sales of Li-ion battery cells are expected to grow exponentially (Figure 24). Their market value increases from 24 bn € in 2017 to about 65 bn € in 2025 [44]. Across all market segments, global production will see an unprecedented growth due to EVs, as the main consumer of Li-ion batteries. EVs are projected to demand 65 – 80 %, 80 – 95 % and 90 – 95% of total production of Li-ion batteries by 2020, 2025 and 2030, respectively, compared with about 55 % today.

Figure 24 Future global sales of main Li-ion battery market segments



Source: JRC based on BNEF [26], Avicenne Energy [44] and IDTechEx [52]. *Note*: *EV* includes passenger light duty vehicles and buses; *Electronics* includes consumer electronics for all studies, power tools and medical in Avicenne Energy, and wearables in IDTechEx; *Stationary storage* includes industrial applications in Avicenne Energy.

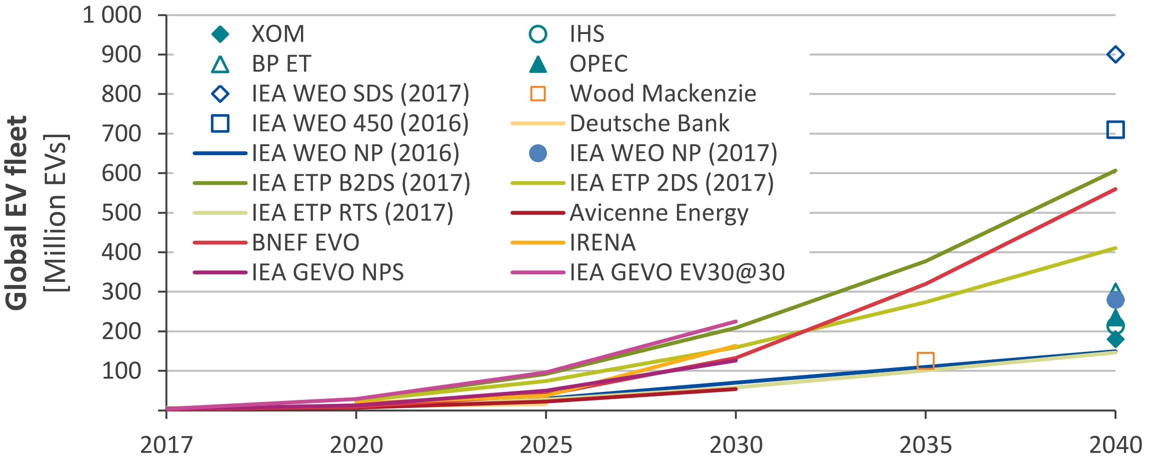
([16]) The difference between annual investments and announcements was about 400 million €/GWh in 2010.

3.1.3 Global market growth of electric vehicles

Figure 25 shows a steep growth of EVs on the road after 2025. Based on a range of global projections, by 2030, the lowest value is about 50 million EVs and the highest estimate is 4 times higher (225 million EVs). The lowest projection reflects the potential deployment of EVs under reference technology development assumptions, captured by the IEA's Energy Technology Perspectives RTS scenario [103]. The highest projection, reflects the ambition that 30 % of the global market share of all vehicles will be captured by EVs [45].

By 2040, the volume increases from about 150 million EVs under reference technology assumptions [103] up to 900 million EVs in ambitious scenarios with respect to decarbonisation, improved energy access and air quality (captured by IEA's World Energy Outlook SDS scenario [63]). The 4-fold and 6-fold difference across scenarios, in 2030 and 2040, respectively, clearly shows the varying perspectives on future EV growth. A scenario review, conducted by the Center on Global Energy Policy (CGEP), concludes that different forecasts have widely disparate views on key underlying drivers of oil demand such as population and economic growth, which could also affect the total number of EVs [104]. In addition, CGEP mentions that forecasts consider the adoption of EVs is encouraged by government policies and technology change, which is reflected in battery costs and is one of the most uncertain factors [104]. Even so, the analysis conducted in the present report points out that even under the most pessimistic projections the size of the EV fleet will multiply by 50 in 2040 compared with today. Moreover, the more ambitious the scenarios in terms of climate targets, the higher the deployment of EVs would need to be, as shown by the number of total EVs in decarbonisation scenarios, due to higher electrification rates. Notably, similar growth is also seen by market scenarios such as the one considered by BNEF [26,105], in which climate targets are not met.

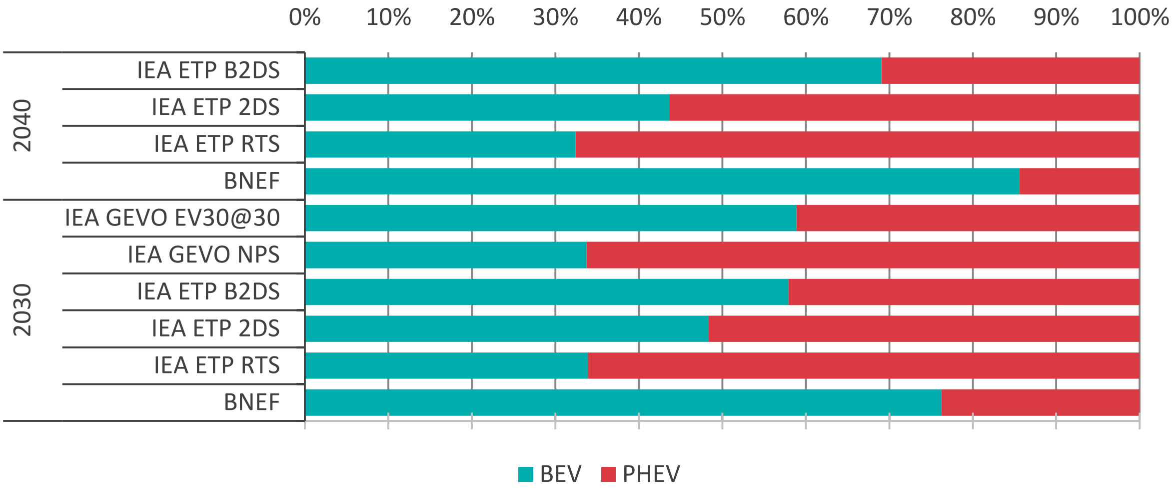
Figure 25 Projections of the global EV fleet over time



Source: JRC based on different studies and scenarios [26,45,47,63,65,103,106–109]. Abbreviations of the studies can be found in the references. *Note*: the fleet includes passenger light duty vehicles (BEV and PHEV) and electric buses.

Another difference across scenarios lies in the composition of the EV fleet. Figure 26 shows that the more ambitious the scenario is in terms of decarbonisation (e.g. IEA ETP B2DS), EV push in the market (e.g. IEA GEVO EV30@30), or favourable market assumptions (e.g. BNEF), the higher the share of BEVs. As the battery capacity of BEVs is higher than that of PHEVs, the associated global manufacturing capacity will be influenced by the composition of the EV fleet. Heavier duty vehicles, and specifically electric buses, could also have an effect on the demand for Li-ion batteries, as they typically require much larger batteries. IEA forecasts the total number of buses to reach 1.5 and 4.5 million units by 2030 in their New Policies and EV30@30 scenarios, respectively [45]. BNEF expects the global electric bus fleet to be somewhere between these values, at 2.3 million buses in 2040 [26].

Figure 26 Share of BEV and PHEV in the global EV fleet according to different scenarios in 2030 and 2040

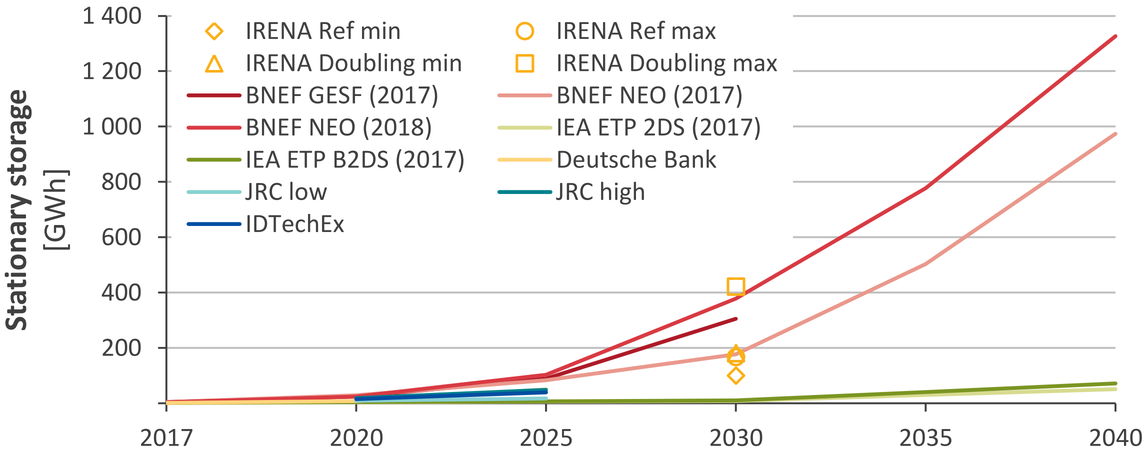


Source: JRC based on BNEF and IEA [26,45,103].

3.1.4 Global market growth of stationary storage

From a niche application today, Li-ion batteries for stationary storage are projected to increase rapidly over time. In the near-term, most projections see an increase by up to an order of magnitude, from about 3 – 4 GWh today to 100 GWh in 2025. Beyond 2025, the steep growth continues: the lowest estimates range from 8 to 100 GWh and the highest estimates reach 400 GWh in 2030, ultimately leading to 1 300 GWh in 2040 (Figure 27). Compared with EV outlooks, fewer studies report on stationary storage (see e.g. Figure 25). Also most forecasts extend up to 2025 – 2030. Overall, the slowest growth is projected by IEA [103], which is possibly due to the fact that their projections do not include residential applications. Highest growth is foreseen by BNEF, which in its latest New Energy Outlook, revised its projections upwards [105].

Figure 27 Projections of total stationary storage installed front- and behind-the-meter globally

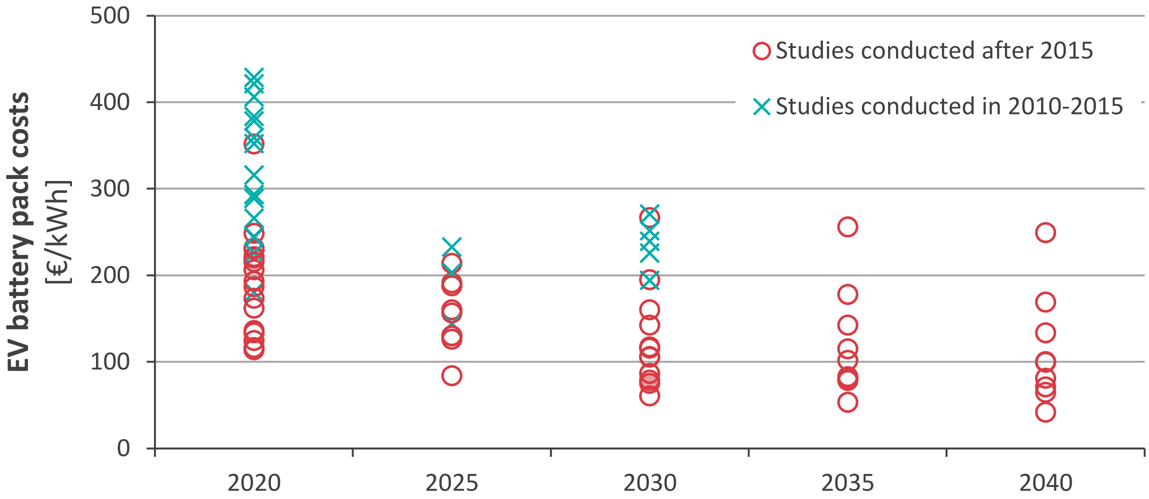


Source: JRC based on various literature sources [31,39,43,52,58,65,83,105]. Abbreviations of the studies can be found in the references. *Note*: IEA [103] is not clear as to whether they include behind-the-meter applications in their projections for storage.

3.2 Future costs of Li-ion batteries for EVs and stationary storage

The average value across cost forecasts of battery packs for EVs taken from literature show a decline from about 250 €/kWh in 2020 to 110 €/kWh in 2040, a trend that is more conservative than recently announced prices at about 200 €/kWh (Figure 28). The range of estimates is rather wide, with values reported from above 400 €/kWh in the short term to as low as 40 €/kWh in the long term. One explanation is that studies published between 2010 and 2015 anticipated the costs to decline but possibly owing to the unforeseen rapid drop of prices after 2015 (see Figure 9) their estimates turn out to be conservative. Another aspect is that some studies refrain from offering a single cost trajectory but provide a set of values based on different assumptions (e.g. slow, moderate and rapid advancement considered in the study of NREL [110], or low, high and the global average value from the IEA World Energy Outlook [63]). As a result, a wide range of values is available in literature when it comes to long-term battery pack costs for EVs.

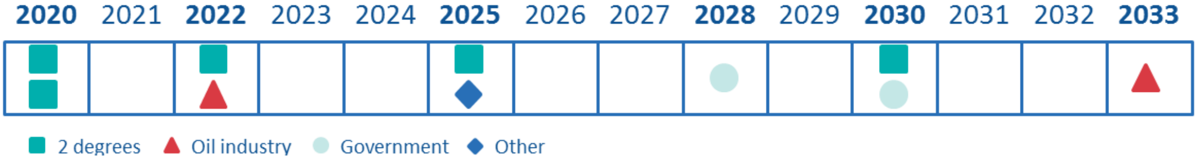
Figure 28 Cost forecasts of Li-ion battery packs for EVs



Source: JRC based on literature sources (NREL [110], IEA [63,103], Schmidt et al. [57], Avicenne Energy [44], Deutsche Bank [65], BNEF [26], and several sources in Nykvist and Nilsson [60] and Berckmans et al. [111]). *Note*: the figure includes the cost target based on SET Plan for 2030 (filled symbol) [23].

Furthermore, there is no consensus as to when batteries may reach price which will bring EVs at parity with internal combustion engine vehicles (e.g. at a set price of 90 €/kWh), as forecasts range from 2020 to 2033 (Figure 29).

Figure 29 Year when EVs are at price parity with internal combustion engine vehicles based on different scenarios



2020	2021	**2022**	2023	2024	**2025**	2026	2027	**2028**	2029	**2030**	2031	2032	**2033**
🟩 🟩		🟩 ▲			🟩 ◆			●		🟩 ●			▲

🟩 2 degrees ▲ Oil industry ● Government ◆ Other

Source: JRC adapted from CGEP [104]. EV battery pack at 90 €/kWh. *Note*: Each symbol indicates a different study. Differentiation between shape and colour is used to characterise the type of the organisation that conducted each study.

Box 1 Approaches used to estimate costs of Li-ion batteries

1. Detailed engineering studies

Bottom-up calculations based on each cost component required to produce specific battery types according to manufacturing process flows. This approach takes into account fixed and variable expenses such as material and energy costs, direct labour, plant investment costs, research and development, general sales and administration, overhead, which are parameterised based on the manufacturing scale and the plant's annual output. The estimated costs are representative for a specific battery (e.g. power, energy, type, size, hence also performance) and chemistry (e.g. NMC-111, NMC-811, NCA). The production costs are related with specific assumptions on raw material and energy prices. In this method, costs and performance parameters are correlated. Future costs can be estimated with detailed engineering studies when potential improvements, for example in production processes or material efficiency, are considered. The ANL model [112], Berckmans et al. [111] and today's costs of Li-ion batteries from BNEF [26] are few studies that apply this approach. Other studies simplify their estimation by adding components at a higher aggregation level (e.g. Abdon et al. [113], IRENA [114]).

2. Learning curves

Applying the empirical observation that production costs of a technology decline at a specific rate (learning rate) every time the manufactured capacity doubles, this method estimates top-down the evolution of battery costs over time (e.g. [57,60,89,111]). One challenge is to establish a representative learning rate, as it requires robust historical timeseries on production capacity and costs. The three most prominent recent examples that apply the learning curve method are:

- Nykvist and Nilsson [60], who conducted a systematic review of historical Li-ion EV battery pack costs to determine learning rates.
- Schmidt et al. [57], in which cost trajectories of Li-ion EV battery packs, residential and utility-scale storage systems were assessed, in line with deployment that was derived from energy storage diffusion curves.
- Kittner et al. [89] who analysed the deployment and innovation of batteries using a two-factor learning curve model.

3. Surveys, expectations and announcements

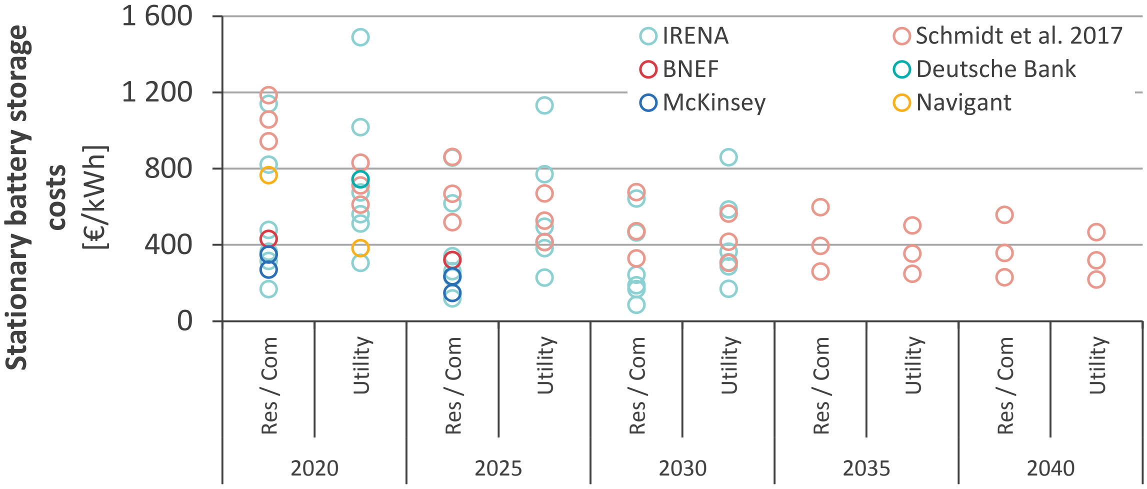
Several consultancies and market research organisations (e.g. Avicenne Energy, Bloomberg New Energy Finance, IDTechEx, Boston Consulting Group) initiate surveys and collect information directly from the producers on the evolution of battery costs. In addition, several companies (e.g. car manufacturers), in support of their strategy, proceed with own announcements on how they expect costs to evolve. These are often near-term forecasts without technical details as they are typically proprietary to the manufacturer. These costs are often quoted in literature, yet, in the absence of technical details and more evidence, they could be highly uncertain or speculative.

4. Levelised cost of storage

Whilst a different metric than capital investment costs and primarily relevant for stationary storage applications, levelised costs of storage are reported by several organisations, taking into account the service provided by the battery (e.g. IRENA [114], Lazard [84]). Results based on this metric are usually provided on a kWh basis, but are not comparable with the capital investment cost metric that is assessed in this report. Unlike levelised costs of energy from conventional technologies, the metrics on storage are not yet established and results vary as new metrics are also being proposed [115].

Cost forecasts of Li-ion battery systems for stationary storage systems show a similar declining trend and wide ranges. Battery packs make up large of part of the total cost. The range is somewhat wider for stationary storage, firstly, because additional components are included (e.g. inverters, BOS) and secondly, because diverse applications call for different battery and system design (e.g. power shaving is a power-designed system compared to self-consumption which is energy-designed). As such, on a kWh basis, power-designed systems (*Utility* in Figure 30) are shown to cost more than energy-designed systems (*Res / Com*, in Figure 30). In addition, studies provide different cost estimates either based on different chemistry (e.g. IRENA [114]), or based on different modelling assumptions (e.g. Schmidt et al. [57]). Another observation is that some studies tend to be more optimistic (e.g. IRENA [114] in Figure 30) than others (e.g. Schmidt et al. [57] in Figure 30). Besides the different method used to estimate costs (Box 1), different system boundaries could also be an explanation.

Figure 30 Cost forecasts of Li-ion battery stationary system storage based on literature

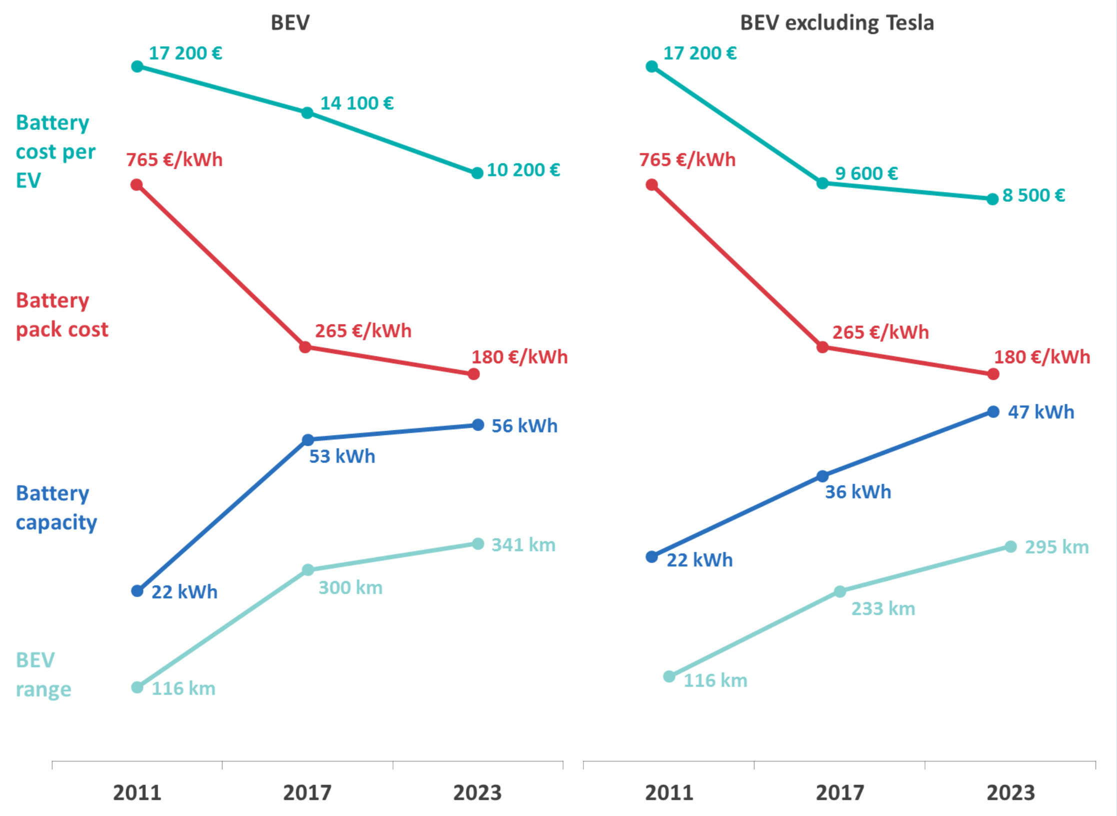


Source: JRC based on IRENA [114], Schmidt et al. [57], BNEF [85], Deutsche Bank [65], McKinsey [86] and Navigant [87]. *Note*: IRENA estimates are based on ranges for all Li-ion chemistries and selected applications (self-consumption as residential and peak-shaving as utility). The size of the inverter is selected accordingly (small-scale for residential and large-scale for utility).

Box 2 Techno-economic performance of EV batteries

Between 2011 and 2017, the techno-economic performance of Li-ion batteries has seen significant improvements (Figure 31). On average, costs of packs have decreased by 65 %. While the capacity of the batteries in EVs more than doubled, the total cost dropped by 10 %. Larger battery size also entails longer ranges, which have more than doubled since 2011.

Figure 31 Historical and near-term Li-ion battery performance improvement of BEVs in western markets (i.e. excluding China)



Source: Historical estimates based on weighted average sales from BNEF [38] and technical specifications from WattEV2Buy [53], High Edge [54] and ITRI [55], future estimates based on technical performance in IRENA [108] and BNEF [26].

Historically, this step change in weighted average costs and performance can be largely attributed to the production of Tesla vehicles, which, compared with other BEVs, have larger battery size and range. Since 2013, Tesla cars represent from about one-fifth to one-quarter of all new BEV sales. Anticipated improvements of new batteries of the remainder of the fleet show that the historical improvements will continue in the near-term.

4 Scenario-based cost trajectories of Li-ion batteries

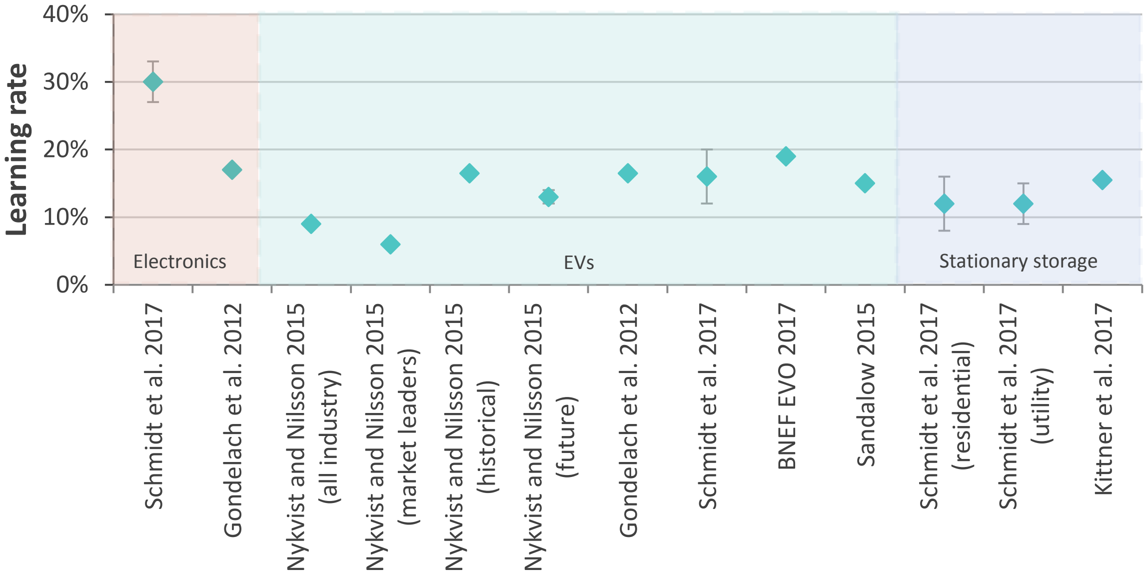
4.1 Method

4.1.1 Learning rates

The costs of energy technologies have been correlated with their cumulative installed capacity as an indication of the experience gained through increased global manufacturing of the technology and its components [40,41]. Researchers and analysts extend this historical correlation to assess top-down how costs of energy technologies may develop in the future. This method is known as learning or experience curve. It combines the historical rate of cost reduction achieved for every doubling of installed capacity of a technology (learning rate) with projections on its deployment over a period of time (for a description of the method see, for example, Tsiropoulos et al. [116]). A technology learning rate is derived from historical data on cost development over time and on manufacturing output or installed capacity. Figure 32 shows different learning rates that have been reported for Li-ion batteries. The period of analysis, the technology boundaries, the metrics used (e.g. cost or price, annual or cumulative production) offer possible explanations as to why the values range. For Li-ion batteries, Schmidt et al. [57] note that learning rates tend to decrease with increasing technology scope.

Learning rates of inverters, a key component of stationary storage systems (section 2.2.2), are reported at 19 % (± 1 %) [8,9,57].

Figure 32 Learning rates of Li-ion batteries for different applications



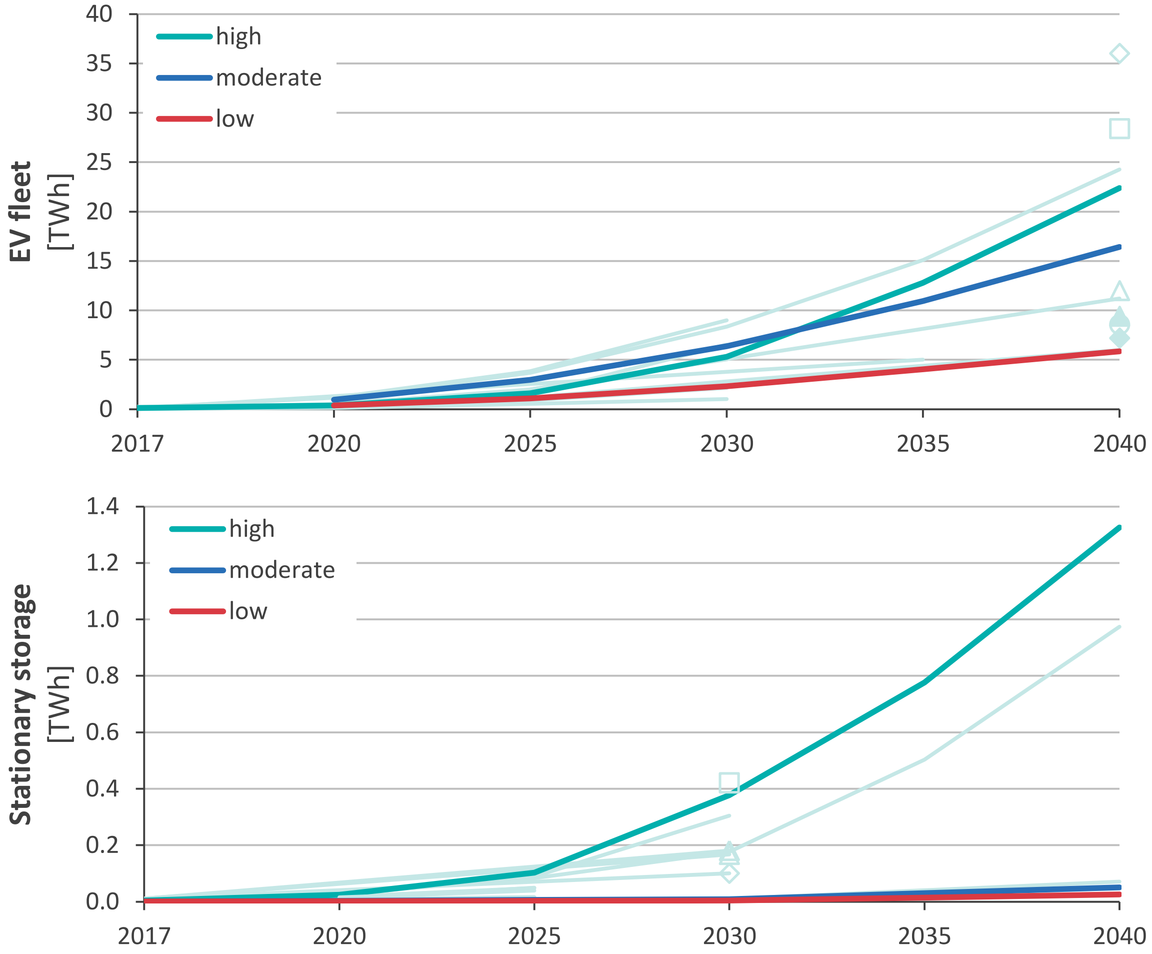
Source: JRC based on literature [57,60,67,89,117,118].

4.1.2 Selected global growth scenarios

Available global growth scenarios of EVs and stationary storage are shown in Figure 25 and Figure 27, respectively. Long-term projections on future deployment of a technology are inherently uncertain, as they are based on different approaches (e.g. market penetration models, energy system models) and critical assumptions therein (e.g. CO_2 emission reduction target, energy efficiency goals, technology costs). Furthermore, the deployment of Li-ion batteries for mobility or stationary storage applications does not occur in isolation from the rest of the energy system. It depends on a number of factors such as the synergies with residential photovoltaics that may boost the deployment of behind-the-meter applications or the competition with other technologies such as fuel cells in the transport sector. In the long-term, dynamics from synergies and competition may prove important. Using deployment projections of EVs and stationary battery storage from distinctly different scenarios provides a range of growth trajectories, which has the advantage of taking system dynamics into account and is consistent across all technologies within each scenario.

To address different possible long-term futures of Li-ion batteries, three global deployment scenarios are selected from literature, which outline growth trajectories of EVs (Figure 25) and stationary storage (Figure 27). The selected scenarios cover a wide range of projections and they are adequately different in terms of technology portfolio and deployment levels of all technologies (Figure 33). The deployment projections for EVs and stationary storage in the *high* scenario (Box 3) are based on the 2018 Electric Vehicle Outlook and the 2018 New Energy Outlook of Bloomberg New Energy Finance (BNEF NEO 2018) [94,105]. Projections in the middle of the range are covered by the *moderate* scenario (Box 4), which is based on the deployment figures of the International Energy Agency's 2DS scenario of the 2017 Energy Technology Perspectives (IEA ETP 2DS 2017) [103]. Finally, the lower end of the range is covered by the *low* scenario (Box 5), which relies on deployment on the International Energy Agency's Reference Technology Scenario of the 2017 Energy Technology Perspectives (IEA ETP RTS 2017) [103].

Figure 33 Selected global growth scenarios for EVs (upper figure) and stationary storage (lower figure)



Note: Global EV fleet battery capacity estimated based on million EVs on the road (Figure 25) and battery capacity of 40 kWh/EV.

Box 3 Description of the high scenario (BNEF NEO 2018)

Among the selected scenarios, the *high* scenario sees the highest deployment of EVs and stationary storage. According to this scenario, market forces drive decisions based on technology costs. EVs gain a significant market share as they gradually come at cost parity with internal combustion engines (EVs are 33 % of the total fleet in 2040). Renewables become increasingly competitive and wind and solar supply almost all new electricity demand globally. Growth in intermittent renewables goes hand in hand with growth in stationary battery storage, which allows more than 1/3 of total demand to be supplied by wind and solar in 2040. The growth in renewables and decoupling of emissions in passenger road transport allows for significant changes in emission profiles of large economies, however, global CO_2 emission reduction goals in line with the Paris Agreement are not met. The deployment projections for EVs and stationary storage are based on the 2018 Electric Vehicle Outlook and the 2018 New Energy Outlook of Bloomberg New Energy Finance [94,105].

Box 4 Description of the moderate scenario (IEA ETP 2 DS 2017)

The world moves towards decarbonising its energy system up to a 2 °C average global temperature increase, with 50 % likelihood, by the end of this century. This challenging transformation reduces emissions from energy use and other sectors. EVs and energy storage participate in a broad technology portfolio, which among other options includes, renewable electricity generation, biofuels in transport, hydrogen, carbon capture and storage (CCS) and demand-side measures (e.g. energy efficiency). Intermittent renewables provide somewhat less than 1/3 of total electricity demand, while baseload and flexible generation from solid fossil fuels, gas and biomass still have a strong presence in the energy mix in 2040, as they can be combined with CCS. Growth of EVs (23 % of the global fleet in 2040) and system storage is based on the International Energy Agency's 2DS scenario of the 2017 Energy Technology Perspectives [103].

Box 5 Description of the low scenario (IEA ETP RTS 2017)

The world moves from earlier "business-as-usual" paradigms to more ambitious pathways with respect to emission reduction, yet no major transformation takes place before mid-century. Nationally Determined Contributions on CO_2 emission reduction, pledged by the parties under the Paris Agreement are met, but they fall short in reaching the level of the internationally agreed climate change mitigation targets. In this context, electrification of passenger road transport is limited (EVs are 7 % of the total fleet in 2040), penetration of intermittent renewables increases only up to 15 % and fossil fuels still dominate the global electricity mix. This scenario is used as a baseline against which the impacts of growth of EVs and stationary storage can be measured. It is based on the International Energy Agency's Reference Technology Scenario of the 2017 Energy Technology Perspectives [103].

4.1.3 Implicit assumptions

Combining learning rates with global deployment projections of EVs and stationary storage, implicitly assumes that Li-ion batteries are the winning technology that take up the entire share in these markets, across all scenarios (*high*, *moderate*, *low*). Even if lead acid batteries dominate the broader electrochemical storage market today (including energy storage, telecommunications, industrial and other applications), Li-ion is expected to be the leading technology by 2025 [119]. Li-ion technologies represent 81 % of electrochemical energy system storage (in terms of power capacity; section 2.1.2). In the longer term, Li-ion batteries are suitable for most services in the energy system; other battery storage technologies will ultimately compete on costs.

Besides applications in mobility, more explicit assumptions on stationary storage are that: a) Li-ion stationary storage benefits from the learning, hence the cost reduction, achieved in battery packs driven by the market growth of EVs (spill-over learning), b) costs of PCS components reduce based on learning in production of inverters, in line with the growth of photovoltaics in each of the selected scenarios, c) costs of the remaining components (e.g. BOS, EPC, EMS) reduce based on growth and learning rate of stationary storage applications only. As benchmark power-designed, energy-designed systems and residential batteries the cost structures of BNEF are assumed [85,105] (see also Figure 18 and Annex 3).

The lifetime of Li-ion EV batteries is assumed to be 10 years, which is reasonable taking into account that many manufacturers provide warranty for 8 years and that significant effort is made by both cell manufacturers and automotive producers to make robust and long-lasting batteries. The lifetime of stationary storage is assumed to be 20 years. The majority of Li-ion storage projects in US DOE's database have a lifetime between 15 and 20 years [56].

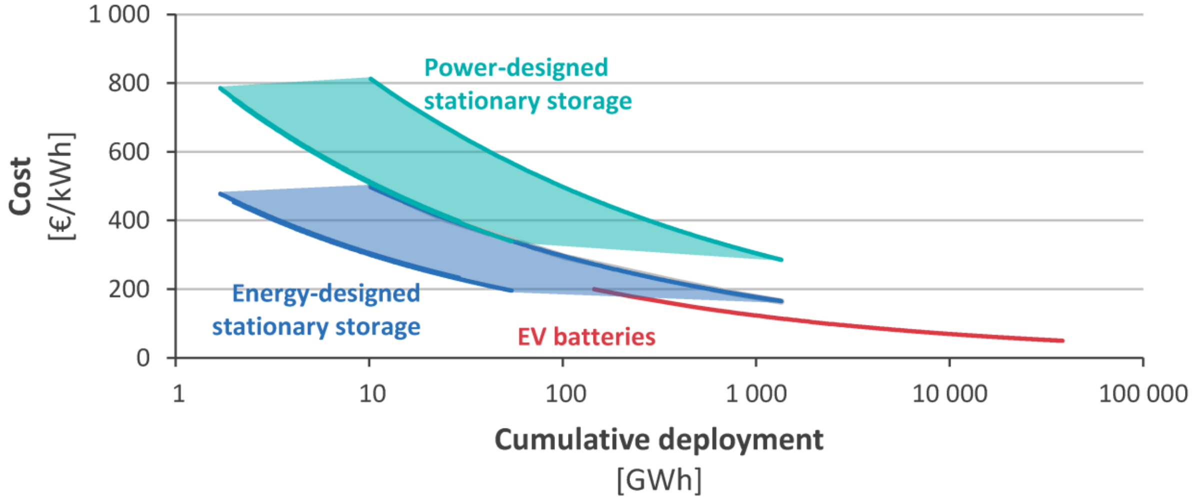
The influence of several of these assumptions on the cost trajectories is assessed in detail in section 4.3.

All data and parameters used to estimate cost trajectories of Li-ion batteries for mobility and stationary storage applications can be found in Annex 3.

4.2 Cost trajectories

The cost trajectories of Li-ion batteries estimated with the learning curve method are presented as a function of cumulative deployment (Figure 34) and time (Figure 35, Figure 37-Figure 38, Figure 40).

Figure 34 Learning curves for Li-ion batteries for EVs and stationary storage systems



Note: cost reduction of stationary storage is estimated based on total deployment of Li-ion cells (i.e. for stationary storage and EVs), while the figure presents the deployment range associated with stationary storage only.

The main remarks on cost trajectories of **Li-ion batteries for EVs and stationary storage** as a function of cumulative deployment (Figure 34) are the following:

- The costs of power-designed and energy-designed stationary storage systems converge with increasing installed capacity, due to the changing cost structure over time (lower contribution of battery packs thus increasing contribution of other components; see also Figure 39).
- The learning rate of EV packs is 16 % and is based on literature [57]. The combined learning rate of energy-designed stationary storage systems ranges between 14 and 16 %, while for power-designed systems it ranges between 14 and 15 %.
- The effect of spill-over learning is shown by the steeper decline of stationary storage costs compared with EV costs, albeit the lower learning rate and range of cumulative deployment of the former.
- The SET Plan target for stationary storage system costs at 150 €/kWh [23] could be attainable at high global deployment of EVs and more than 1 TWh of stationary storage deployed globally. It could be beneficial to define separate targets for power-designed systems, as a significant cost difference is noticed when compared with energy-designed systems.

As regards the cost trajectories of **Li-ion battery packs for EVs** as a function of time (Figure 35) the main remarks are the following:

- Costs are reduced by more than 50 % by 2030 and by 63 to 75 % by 2040, compared with today, depending on the storyline. That is a 4 to 6 % reduction in cost when the fleet size increases between 16 and 25 % on an annual basis.
- Early in the time horizon, costs decrease faster in the *moderate* scenario, possibly due to the push for EVs in order to achieve greenhouse gas emission mitigation targets. After 2030, EVs penetrate much faster in the *high* scenario, as they become competitive in more regions, and costs decline faster than in the *moderate* scenario. Overall, the cost trajectories in these scenarios are similar.
- Costs decrease relatively quickly, yet more conservatively in the *low* scenario. This indicates that EV penetration is the main cost reduction driver. In this scenario costs remain above 100 €/kWh until 2030. This may impede EV deployment at large scales and delay any efforts for transport decarbonisation.
- The costs estimates fall consistently within the lower-end of literature results.
- The SET Plan target for Li-ion EV battery pack cost (75 €/kWh by 2030 [23]) is feasible in both *high* and *moderate* scenarios. This entails fast ramp-up of Li-ion manufacturing capacity, of about 2 gigafactories globally per year until 2030 (Figure 36) (17). Should unfavourable conditions prevail (e.g. *low* scenario), meeting the SET Plan cost target seems more likely around 2040.
- Based on these cost trajectories and annual sales, the global Li-ion battery market for EVs could reach 40 – 55 bn €/yr in 2025. For European production this could entail a growth from about 450 M€/yr in 2017 to 3 – 14 bn €/yr in 2025. Globally, the market size may exceed 200 bn €/yr by 2040.

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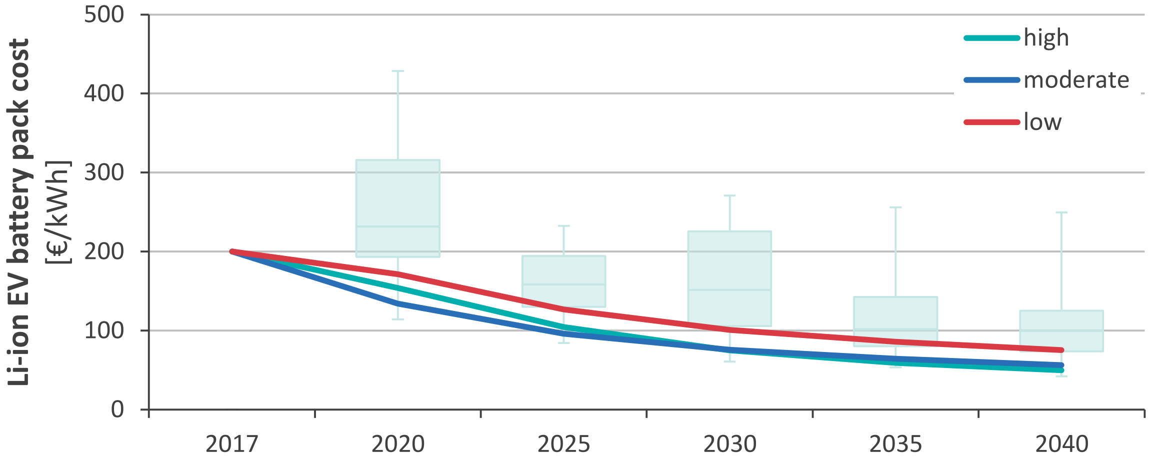
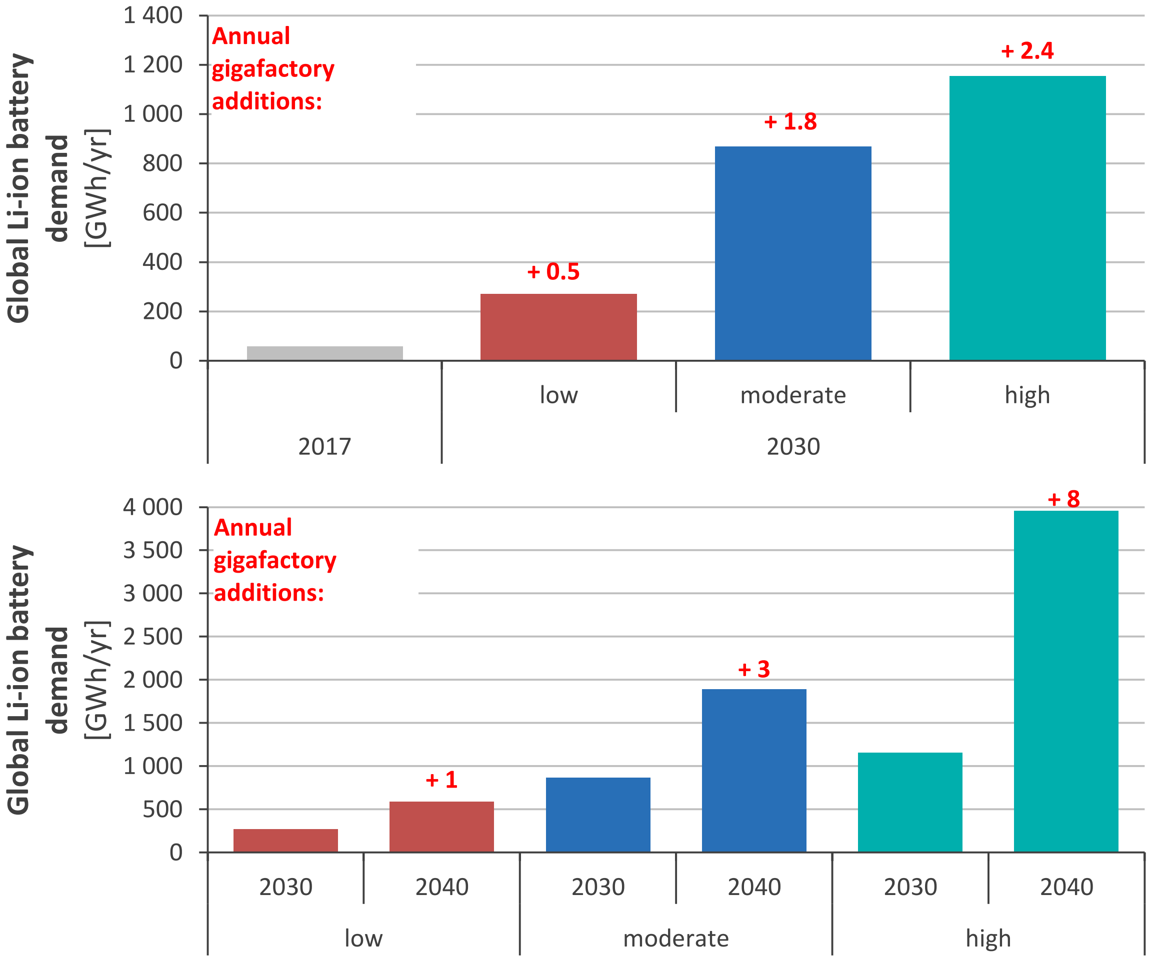
(17) Assuming 35 GWh/yr per Gigafactory. After 2030 the gigafactory additions increase significantly up to 8 gigafactories per year to meet the demand in 2040 in line with the *high* scenario.

Figure 35 Cost-development of Li-ion battery packs for EVs over time based on three different deployment scenarios



Note: literature estimates are represented by the boxplots and include values presented in section 3.2.

Figure 36 Global ramp-up of manufacturing capacity of Li-ion cells and annual gigafactory additions in each scenario to 2030 (upper figure) and from 2030 to 2040 (lower figure)

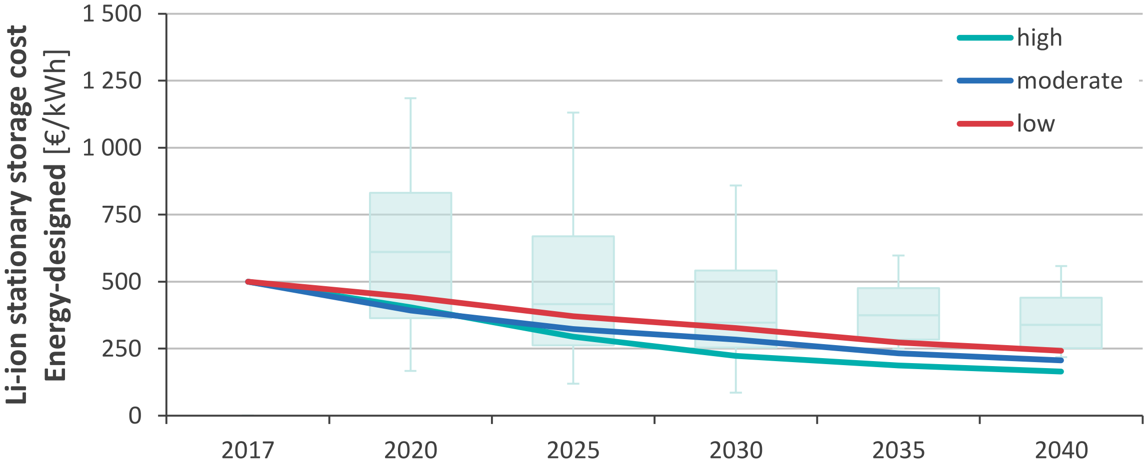


Note: assuming 35 GWh per gigafactory.

On cost trajectories of **Li-ion stationary storage systems** as a function of time (Figure 37 and Figure 38) the main findings are:

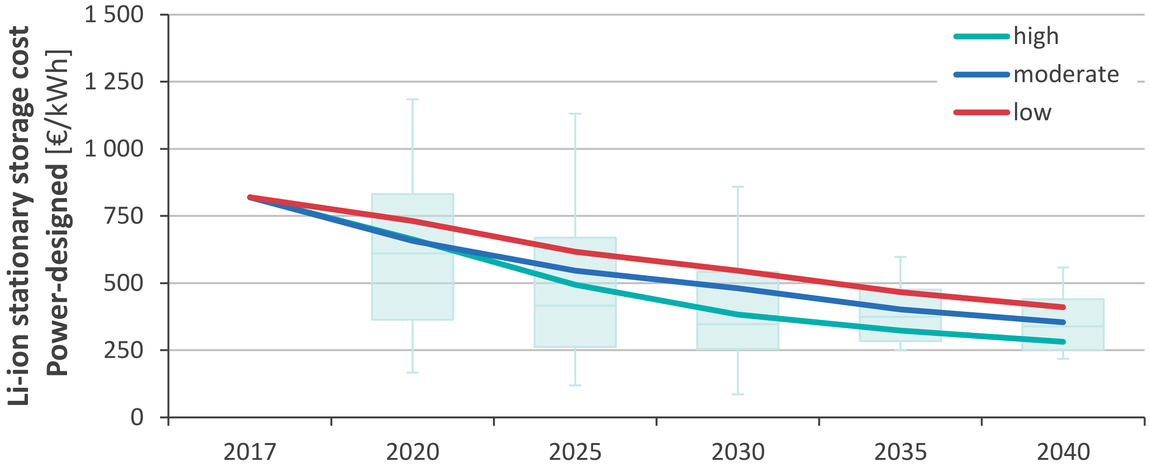
- By 2030, costs are lower between 30 and 55 % compared with today. By 2040 they are lower by up to 66 % compared with today, depending on the storyline. That is an annual cost decline of 3 to 5 % when installed capacity increases 13 to 24 % per year.
- In the short-term (2020-2025) there is no substantial difference between the *high* and the *moderate* scenario. Thereafter the decline in the *high* scenario outpaces that of *moderate*.
- The difference in costs between scenarios reaches 35 – 40 €/kWh for energy-designed and 55 – 70 €/kWh for power-designed systems in 2040. Compared with system costs of stationary storage today this may not seem significant, but it becomes substantial considering that it could represent 15 to 25 % of total system costs in 2040.
- Costs below 200 €/kWh can be reached for energy-designed systems after 2030 under the scenario with the highest deployment of batteries for EVs and storage due to spill-over effects (*high* scenario). For comparison, the cost target of SET Plan is at 150 €/kWh at a system level for 100 kW [23].
- For energy-designed systems, the costs fall within the lower range of values found in literature. After 2035, the cost estimates of this report are lower than other literature estimates. For power-designed systems, estimates fall within the range of costs in reported in literature. There is limited publicly available data beyond 2030 to draw more detailed conclusions.
- Over time, all major cost components of stationary system storage decline (Figure 39), with major reduction noticed in battery packs (around 75 % by 2040) and by a similar rate in PCS and other components (about 60 % by 2040). These downward trends change the cost structure of stationary storage systems over time and, by 2040, BOS, EPC and other soft costs become the major cost component.
- Li-ion battery pack costs are set to decrease based on deployment of EVs, and PCS costs also steeply drop based on growth of inverters of photovoltaics. The next frontier to reduce costs of stationary storage further are BOS hardware, EPC costs, and soft cost components (e.g. land acquisition).

Figure 37 Cost-development of Li-ion battery for utility scale energy-designed stationary storage systems (C-rate 0.25) over time based on three different deployment scenarios



Note: literature estimates are represented by the boxplots and include values presented in section 3.2.

Figure 38 Cost-development of Li-ion battery for utility scale power-designed stationary storage systems (C-rate 2) over time based on three different deployment scenarios



Note: literature estimates are represented by the boxplots and include values presented in section 3.2.

Figure 39 Cost structure and cost structure development of utility scale stationary storage systems over time in the high scenario

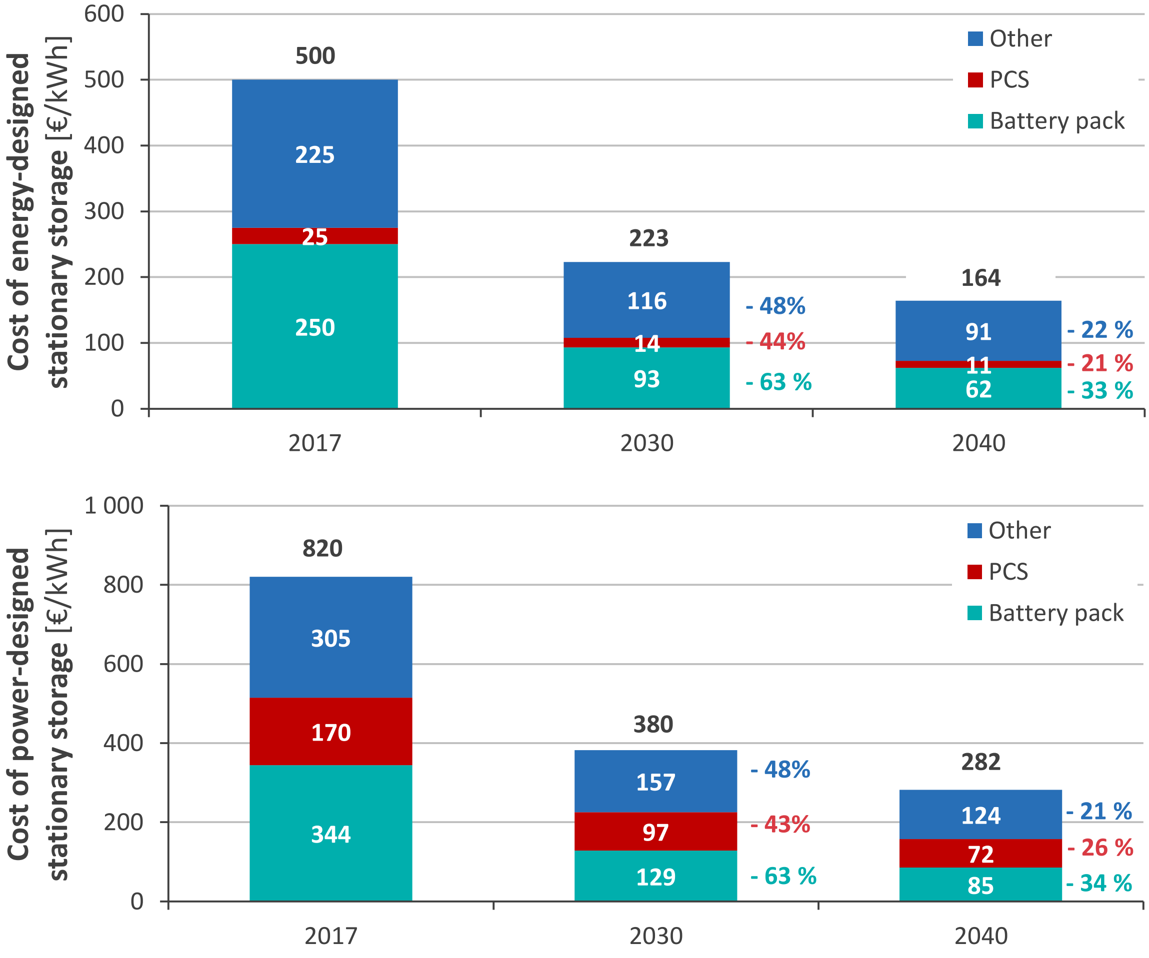
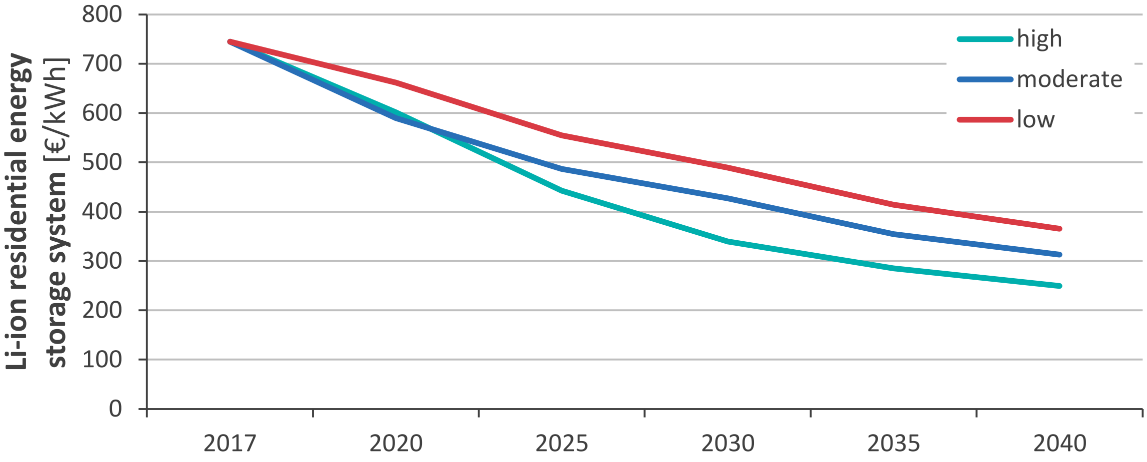


Figure 40 Cost development of Li-ion residential energy storage (C-rate 0.35)



The reduction rate of **residential storage** is assumed to be the same with that of utility-scale systems (18). Apart from the different absolute cost levels (determined largely by the C-rate; see Note in Figure 18), the contribution of each major component also differs in the three systems (energy-designed and power-designed utility-scale systems and residential batteries). Ultimately, however, the cost reduction over time in relative terms is found to be similar for the stationary storage systems and steeper for battery packs. In absolute terms, the savings are more substantial for residential and power-designed systems (on a kWh basis).

4.3 Sensitivity scenarios

Anticipated developments on Li-ion battery performance or on system characteristics may influence the main assumptions that were used to estimate the reference cost trajectories (section 4.2). To provide a holistic view, Box 6 presents six additional scenarios that capture the sensitivity of the reference costs.

Results show that the assumed learning rate is by far and foremost the most influential assumption across all systems assessed in this report, as it may lead to a cost difference of up to 45 % for EV packs and up to 38 % for stationary storage systems, compared with the reference costs. This highlights the need of using well-established learning rates when applying the method on Li-ion batteries, and updating them as necessary, because combined with high growth projections of EVs the ultimate costs may diverge significantly. This observation is further supported by the scenario on learning only at cell level, which is a major cost component of Li-ion batteries. The scenario assumes the high historical learning rates observed for Li-ion cells for electronics (i.e. 30 % [57]) and applies them on cells for EVs and stationary storage. It shows that, decomposing this technology to a more granular level but using learning rates of similar yet not identical applications, could drastically alter the findings (more than 30 % lower costs were found in reference results in 2040).

Another key assumption of the method is that the experience gained due to growth in manufacturing of Li-ion cells and packs for EVs spills over to stationary storage. This assumption proves influential as costs of energy-designed systems may be higher by about 20 to 30 % and of power-designed systems by about 18 to 25 %. Influential as

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(18) Based on the methodology applied in the present report, each cost component (battery pack, inverter, other) reduces at the same rate across the different stationary storage systems. However, the overall reduction rate differs between the storage technologies due to the different contribution of these components. The cost contribution and the cost levels are based on BNEF [85,105].

this assumption may be, it is unlikely that Li-ion battery manufacturing will be isolated to their respective markets, as even today, they are produced by the same companies.

Box 6 Description of what-if and sensitivity scenarios

1. Learning rates

The learning rate is a parameter that directly affects the results as it is the rate used to estimate the cost reduction over time. In this set of sensitivity scenarios, cost trajectories are assessed under the same growth assumptions (section 4.1.2) with the reference results but for high and low learning rates of Li-ion battery packs, inverters and stationary storage systems (Table 13, Annex 3).

2. Effect of battery size in manufacturing capacities

The total annual manufacturing volume of Li-ion batteries is based on the assumption of an average size of 60 kWh for BEVs and 20 kWh for PHEVs in 2040 (Table 12, Annex 3). As manufacturers are moving towards larger battery sizes, this assumption may prove important and additional capacity may be required if battery sizes increase more than what is assumed. This scenario assesses two widely different situations: a) the battery size increases to 90 kWh for BEVs and 30 kWh for PHEVs (high scenario) and b) the battery sizes remain as today (low scenario).

3. Battery lifetime

The lifetime of batteries is directly related to the rate at which EVs, residential or utility scale batteries are replaced by new capacity. At a high lifetime scenario, fewer batteries are replaced thus cumulative production is lower compared with a low lifetime scenario where replacements occur more frequently and cumulative production will need to be higher (Table 10, Annex 3).

4. Second life of batteries

According to this scenario, all Li-ion EV battery packs can be used in stationary storage applications after the end of their life in an EV (1st life with duration of 10 years). As such, the demand for Li-ion batteries from energy storage applications is largely covered by the primary EV market. As a result, the total production of Li-ion batteries is lower compared with the reference scenarios. In this scenario it is assumed that used EV battery packs are re-sold at 50 % of the cost to Li-ion battery pack manufacturers for energy storage (this cost is assumed to account for complete revamping of the used EV battery pack).

5. Spill-over learning

In this scenario it is assumed that manufacturing of Li-ion batteries for stationary storage is fully independent from the production of EV batteries. Similarly, learning from inverters of photovoltaics does not transfer to PCS components of storage systems. Learning effects on cost of batteries for stationary storage depend only on the deployment of energy storage applications and not on EVs.

6. Cell level learning

This scenario aims to capture that learning is primarily relevant at a cell level, where production scale, material substitution, improved performance and synergies due to multiple applications may take place. Li-ion cell manufacturing for EVs and storage benefits from experience also from electronics production. In this scenario learning rates for electronics apply for Li-ion cells in all segments. For the remaining components (i.e. pack, inverter, rest for stationary storage) reference learning rates apply (Table 13, Annex 3).

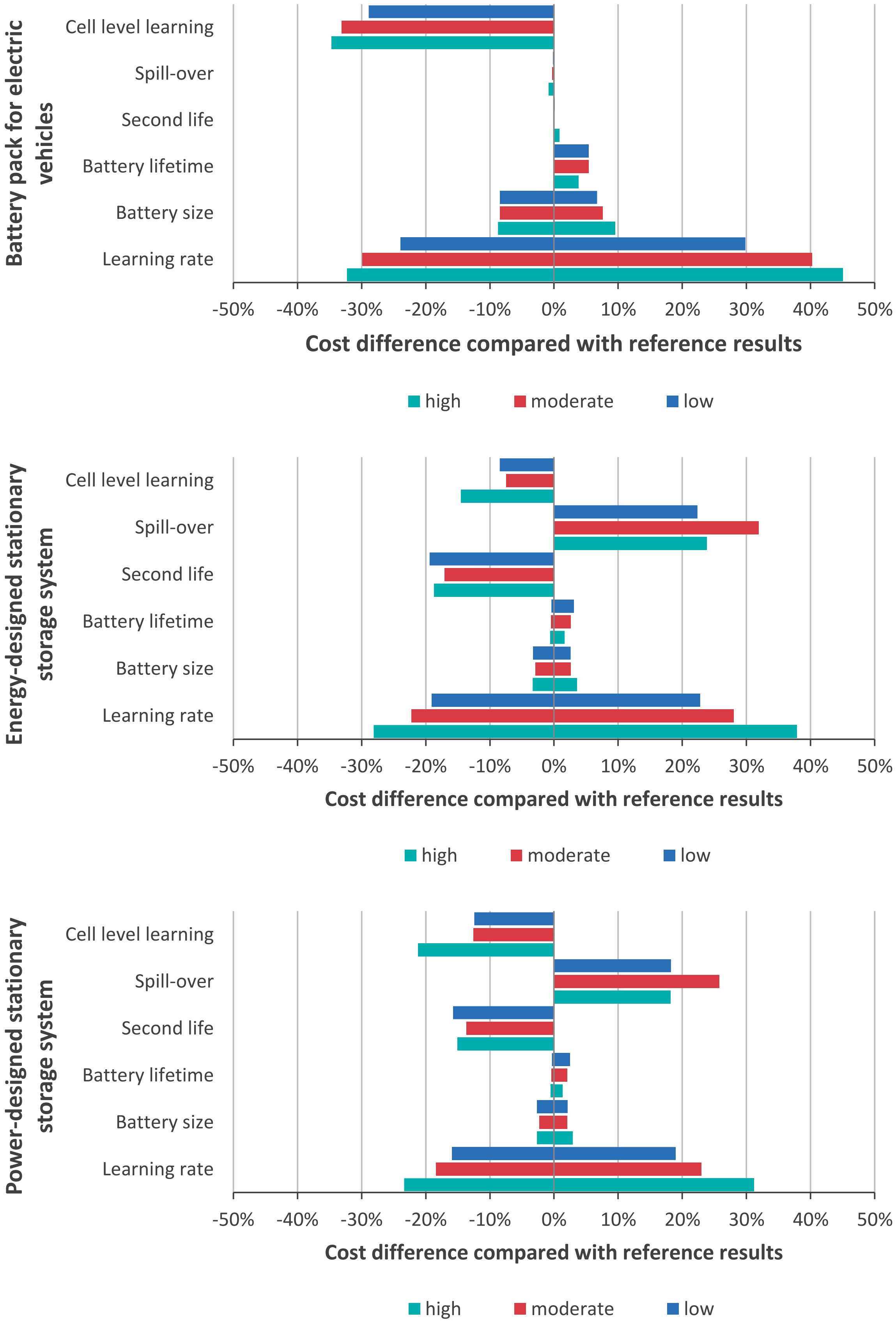
Re-using Li-ion EV battery packs for stationary storage applications, lowers the costs of the latter due to lower purchasing costs of battery packs by stationary battery storage producers ([19]). As such, the results for this scenario are entirely driven by the cost of the used EV battery pack (here assumed that refurbished batteries come at a 50 % cost of a new battery pack). This reveals the need for estimating cost effects and life cycle cost of EV batteries when used for other applications more precisely. Moreover, second life of electric vehicle batteries contributes towards improving their sustainability performance and facilitating circular economy [120].

Other assumptions, such as the evolution of the battery size or the lifetime of Li-ion batteries are not found to affect the results on costs as the overall difference is less ± 10 %.

The absolute range of results across the sensitivity scenarios is shown in Annex 4. Figure 41 summarises the results.

([19]) The issue of second life of EV batteries is acknowledged to be very complex. There are indications that refurbished battery packs may be suitable for a limited number of energy storage applications (such as UPS, frequency regulation and voltage support) and may just as well be re-directed to mobility applications; the development of Vehicle-to-Grid applications may have an impact on the EV battery life and could as such influence the second life potential [129]. Nevertheless, the overall effect of lower required manufacturing capacity thanks to re-deployment of the EV batteries in various second life applications would remain and results of this analysis are not expected to vary significantly.

Figure 41 Effects of what-if and sensitivity scenarios on the reference cost estimates



5 Conclusions

Li-ion batteries are seen as the technology that can help decarbonise transport, lift the penetration levels of intermittent renewable energy and offer a competitive edge to the EU's industry in the Li-ion battery value chain. Batteries, including Li-ion, are recognised as a key enabling technology for the energy transition of the EU under the Energy Union and as such, they are they are specifically mentioned in several policy initiatives addressing transport [2,13–15], raw materials [19–21] and energy [5] economic sectors, EU industrial policy [16] and Research and Innovation in the EU [22–24]. The strategic importance of batteries for the EU is further demonstrated by the formation of the European Battery Alliance [25]. Until recently, costs of Li-ion batteries for mobility and stationary storage applications have been one of their barriers to their large scale deployment. The cost reduction over the last two years, largely owing to experience from electronics and surge of EV sales, raises expectations that it will continue into the future, ultimately leading to penetration of electric vehicles and stationary storage in great numbers. Based on announcements, the global Li-ion cell manufacturing capacity is expected to quadruple by 2021 or even increase six-fold by 2022 compared with 2017. In the longer term, studies estimate that 150 to 900 million EVs may be on the road by 2040, which is about two to three orders of magnitude higher compared with today. Over the same period, stationary storage may reach up to 1 300 GWh, compared with 3 – 4 GWh today. These projections point towards a potentially significant market growth but also to diverging views about the future. These projections depend on the direction the world will take, for example, on action against climate change, or on when and how steeply costs will decline. Despite the near-term announcements, global manufacturing capacity is subject to uncertainty in the longer-term. Future costs of Li-ion batteries are directly influenced by this uncertainty to the extent that their production costs depend on economies of scale and the cumulative manufacturing experience gained globally. In turn, technology costs and cost projections are a fundamental parameter that feeds in the policy process.

Focusing on Li-ion batteries as the family of batteries for mobility and stationary storage applications of today and the near future, this report contextualises their potential cost trajectories based on the annual production output which is derived from global energy scenarios up to 2040. To do so, this report operationalises the learning curve method, which combines the historical rate of cost reduction achieved for every doubling of installed capacity of a technology (learning rate) with projections on its deployment over a period of time.

The demand for EVs and stationary storage is based on three scenarios, namely *high*, *moderate* and *low* that cover a range of possible futures. The *high* scenario sees the highest deployment of EVs and stationary storage, assuming that in the longer-term market forces drive decisions based on technology costs. The storyline of the *moderate* scenario is focused on CO_2 emission reduction. It sees a strong growth of EVs to decarbonise the transport sector, yet lower than in the *high* scenario, possibly due to the role of biofuels in reducing road transport emissions. In the power sector, several technologies compete as low carbon energy solutions (e.g. CCS, biomass, intermittent renewables) and the role of stationary storage is less pronounced compared with the *high* scenario. Finally, based on the *low* scenario, the world is at a standstill when it comes to further action against climate change. As a result, sales of EVs and stationary storage are limited. In each of these scenarios, the global manufacturing capacity required to meet the annual demand is enormous. By 2040, almost 4 TWh would be sold annually in the *high* scenario, around 2 TWh in the *moderate* scenario, and 600 GWh would be needed in the *low* scenario, compared with about 60 to 70 GWh of annual sales in 2017. This translates to about 110, 55 and 15 operational Li-ion battery gigafactories in each scenario, respectively, by 2040 (assuming that the annual production capacity of a gigafactory is 35 GWh). At these scales, next to anticipated improvements in Li-ion cell chemistries, optimisation of manufacturing processes, standardisation of design and possibly vertical integration of plants, the costs of Li-ion battery pack for EVs and stationary storage could fall drastically, as also implied by recent literature.

The present report shows that by 2030, Li-ion EV battery packs could come at least at half their cost of today. By 2040 the cost could drop another 50 %, ultimately reaching 50 €/kWh. These cost trajectories are in line with most recent estimates of other studies. The SET Plan target for Li-ion EV battery pack cost (75 €/kWh by 2030 [23]) is feasible in both the *high* and *moderate* scenarios. This entails fast ramp-up of Li-ion manufacturing capacity, of about 2 gigafactories globally per year until 2030. Should unfavourable conditions prevail (e.g. *low* scenario), meeting the SET Plan cost target seems more likely around 2040. If the demand of cells increases rapidly in the following years, there is the caveat that existing and under construction manufacturing capacities may not be enough to cover global demand. Shortage of batteries may result in temporary increase their price above the costs projected in the present report. Similar situation may result from shortage of mining capacity for the critical materials (e.g. cobalt).

As EVs drive the demand for Li-ion battery packs, cost reduction spills over to stationary storage systems, but somewhat slower due to the contribution of other major cost components (e.g. inverters, BOS hardware, soft costs). Overall in 2040, in the *high* scenario, costs of stationary storage systems may be lower by two-thirds compared with today. Costs of inverters may decrease by more than half (20) benefiting from the strong deployment of photovoltaics. BOS hardware, soft costs and other cost components may reduce up to 60 % by 2040 but only in the *high* scenario, in which stationary storage sees strong growth. In the *moderate* and *low* scenarios these costs reduce less than 50 %. As such, BOS and other soft costs become an area to look further into for cost reduction potential to lift barriers that may occur in slower growth futures. Ultimately, stationary system storage costs range between 165 and 240 €/kWh for energy-designed utility-scale systems, between 280 and 410 €/kWh for power-designed utility-scale systems and between 250 and 365 €/kWh for households. Results show that costs below 200 €/kWh can be reached after 2030 for energy-designed systems in scenarios with high deployment of EVs and stationary storage, due to spill-over effects (*high* scenario). For comparison, the SET Plan cost target for stationary storage is 150 €/kWh at a system level and could be attainable at high global deployment of EVs and more than 1 TWh of stationary storage installed.

Based on inventories and the historical average of commodity prices, materials for Li-ion battery packs may cost around 30 €/kWh. In today's cost structures, materials represent between 60 and 75 % of the total cost, which entails that Li-ion battery packs may ultimately cost 40 – 50 €/kWh. As such, the lower bound of the cost estimated in the present report (i.e. 50 €/kWh by 2040) seems feasible. Economies of scale could reduce capital cost, standardisation and automation could limit operating and labour costs, and improved Li-ion chemistries could further reduce the demand for materials, hence overall costs.

The learning curve approach that is used in the present report has, however, its limitations [43]. For instance, it is not suitable to foresee future step changes induced by disruptions, spill-over from other sectors or commodity price changes. Furthermore, it does not capture market distortions, which possibly characterise even today's Li-ion market, such as lower prices due to overcapacity, predatory pricing, or dumping (as was the case with solar panels). Moreover, the learning curve method generally estimates a monotonous cost reduction, which increases or slows down based on the demand projections in the scenarios.

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(20) On a kW basis.

Box 7 Main take-away messages

Wide-spread deployment of electric vehicles will lead to a rapid decrease of Li-ion battery costs in the near term

- Cost levels between 75 and 100 €/kWh can be reached in 2025 – 2030, indicating the feasibility of the cost targets set by the SET Plan.
- At these cost levels, massive deployment of electric vehicles can be expected globally. By 2030, the numbers of electric vehicles on the road will be 10 to 50 times higher than today. Comparable growth levels are expected in Europe: 12 - 19 % of passenger car fleet are expected to be electric.
- These expected developments offer signals to the EU industry, energy system providers (e.g. infrastructure) and other stakeholders (e.g. market design) to anticipate the disruption.

Investment costs of Li-ion battery stationary storage systems will decrease, yet improvements should focus also on non-battery pack system components

- Li-ion battery stationary storage system costs will decrease significantly following the development of batteries for electric vehicles due to spill-over effects.
- By 2040, stationary storage system costs are expected to range between 165 and 410 €/kWh, depending on system configuration.
- High cost share of system storage lies in components such as power electronics, energy management system, balance of plant, system integration and soft costs.
- A significant cost reduction for the mentioned system components would be required, for example, through intensified R&D and increase in manufacturing capacity.

European manufacturing of Li-ion battery cells will increase its share in global production, provided that all announced plans materialise. Supplying domestic demand may prove challenging if capacity does not ramp up after 2025

- In the coming years, the global share of European Li-ion battery cell manufacturing capacity is expected to increase from about 3 % today to 7 – 25 %. Slightly more than half of this capacity will be deployed by well-established Asian Li-ion battery cell producers.
- By 2025, the global market for Li-ion batteries for electric vehicles could reach 40 – 55 bn €/yr. For European production this could entail a growth from about 450 M€/yr (2017) to 3 – 14 bn €/yr (2025).
- Albeit relying on imports today, Europe could cover almost completely its annual demand for Li-ion battery cells by 2025. Thereafter, due to rapid increase of electric vehicle sales, domestic capacity would need a further significant ramp up for Europe to remain self-sufficient.
- The global demand for Li-ion batteries is foreseen to grow also in the long term and may exceed 200 bn €/yr by 2040. To ensure the competitiveness of the EU on the global scene, efforts on increasing the European manufacturing base should continue after 2025.

Re-using and repurposing of Li-ion batteries to energy storage applications after their end of life in electric vehicles contributes to further cost reduction

- In the longer term the volume of batteries from electric vehicles will be sufficient to supply the needs for stationary storage if batteries are re-used.
- Second life of batteries could reduce costs of stationary storage further by about 20 % or 30 to 45 €/kWh.

The learning rates that were used were found to be the single most influential parameter in the assessment. The uncertainty assessment on spill-over effects reveals that they may also prove important, but are unlikely to occur given that Li-ion batteries for mobility and stationary storage applications are produced by the same manufacturers. Finally, if re-purposed Li-ion batteries from the transport sector to energy storage are sold at a fraction of the cost of new batteries, then the effects in stationary storage systems may be more significant than learning. Other assumptions, such as the evolution of the battery size or the battery lifetime, while technically highly relevant, were not found to influence cost projections based on learning.

The top-down cost estimates presented in this report can be complemented by a detailed bottom-up engineering assessment on the influence of material prices, different chemistries and innovations. Nonetheless, the upfront costs of Li-ion batteries for mobility and stationary storage applications presented in this report can be used in further analysis, for example, to determine the total investment costs of different technological options to meet peak demand (e.g. open cycle gas turbines against photovoltaics and different configurations of storage systems), to assess levelised costs of storage and compare different storage technologies or even to assess the competitiveness of the EU industry and value chain on Li-ion batteries taking global developments into account.

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List of abbreviations and definitions

BEV	Battery Electric Vehicle (or fully electric vehicle)
BOS	Balance Of System
CCS	Carbon Capture and Storage
CGEP	Center on Global Energy Policy
EBIT	Earnings Before Interest & Tax
EMS	Energy Management System
EPC	Engineering, Procurement and Construction
EV	Electric Vehicle
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
Li-ion	Lithium ion
NCA	Nickel Cobalt Aluminium oxide
NMC	Nickel Cobalt Manganese oxide
PCS	Power Conversion System
PCT	Patent Cooperation Treaty
PHEV	Plug-in Hybrid Electric Vehicle
RES	Renewable Energy Sources
SET Plan	Strategic Energy Technology Plan
US DOE	United States Department of Energy

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Annexes

Annex 1. Cost components and cost boundaries of Li-ion batteries

Table 3 Grouping of EV producers per country

China	Europe	USA	Japan	Korea
BAIC	Audi	Chevrolet	Mitsubishi	Hyundai
BYD	BMW	Ford	Nissan	Kia
BYD-Daimler	Citroen	Tesla	Toyota	
Changan	Fiat			
Chery	Mercedes			
DongFeng	Opel			
Geely	Peugeot			
Hawtai	Porsche			
JAC	Renault			
Jiangling	Volkswagen			
Kandi	Volvo			
SAIC				
Zotye				

Annex 2. Cost components and cost boundaries of Li-ion batteries

Table 4 Main raw materials in NMC battery packs based on Olivetti et al. [77] and BNEF [26] in kg/kWh (1)

	NMC-111	NMC-811	Main use
Nickel	0.392	0.75	Cathode
Manganese	0.367	0.088	Cathode
Cobalt	0.394	0.094	Cathode
Lithium	0.139	0.111	Cathode, electrolyte
Graphite	1.2	1.2	Anode
Copper	1.4	1.4	Anode, electronics
Aluminium	1.2	1.2	Casing, cooling system

(1) Excluding mainly the separator and plastic components.

Table 5 Historic prices of main raw materials of NMC battery packs in €/t [121,122]

	8 year average (2010-2017)	Historical high (2010-2017)
Nickel	15 660	23 288
Manganese	2 400	3 537
Cobalt	32 380	49 285
Lithium carbonate (1)	5 448	8 387
Graphite	1 294	2 700
Copper	6 718	8 969
Aluminium	1 882	2 440

(1) Lithium carbonate prices were converted to lithium based on 5.3 kg lithium carbonate/kg lithium [123].

Based on the material requirement in Table 4 and the prices in Table 5 it is estimated that NMC-111 materials cost from 47 €/kWh (historical average) to 83 €/kWh (historical high) and NMC-811 materials cost from 31 €/kWh (historical average) to 48 €/kWh (historical high).

Annex 3. Parameters and detailed input assumptions

Scenario assumptions

Table 6 Deployment scenarios for EVs, in million EVs

	2020	2025	2030	2035	2040	Source
High	10	42	134	322	562	BNEF [26]
Moderate	23	74	160	274	410	IEA [103]
Low	9	27	58	101	146	IEA [103]

Table 7 Deployment scenarios for stationary storage, in GWh

	2020	2025	2030	2035	2040	Source
High	25	103	378	777	1 326	BNEF [105]
Moderate	4	6	8	30	51	IEA [103]
Low	2	3	4	15	25	(1)

(1) Assumed as half of the deployment of stationary storage in the moderate scenario.

Table 8 Deployment scenarios for photovoltaics, in GWh

	2020	2025	2030	2035	2040	Source
High	751	1 346	2 137	3 323	4 524	BNEF [105]
Moderate	564	885	1 321	1 846	2 354	IEA [103]
Low	498	551	736	919	1 115	IEA [103]

Table 9 EV fleet composition over time in the selected scenarios (based on the total fleet)

		2020	2025	2030	2035	2040	Source
High	Passenger BEV	61 %	70 %	75 %	80 %	85 %	BNEF [26]
	Passenger PHEV	31 %	27 %	23 %	19 %	14 %	
	Electric buses	7 %	3 %	1 %	1 %	0.5 %	
Moderate	Passenger BEV	55.5 %	52 %	48 %	44 %	43 %	IEA [103]
	Passenger PHEV	43.5 %	47 %	51 %	54 %	56 %	
	Electric buses	1 %	1 %	1 %	1 %	1 %	
Low	Passenger BEV	51 %	40 %	33%	31 %	32 %	IEA [103]
	Passenger PHEV	48.5 %	59 %	66 %	68 %	67 %	
	Electric buses	0.5 %	1 %	1 %	1 %	1 %	

Techno-economics assumptions

Table 10 Capital investment costs of Li-ion batteries in 2017 and assumed technical lifetime

	Unit	Value			Source
CAPEX					
Li-ion battery pack cost	€/kWh	200			Selected from a range of recent values (Figure 9)
Li-ion stationary storage system, energy-designed	€/kWh	500			BNEF [85]
Li-ion stationary storage system, power-designed	€/kWh	820			BNEF [85]
Li-ion stationary storage, residential	€/kWh	745			BNEF [105]
Lifetime			**Sensitivity**		
			High	Low	
EV battery pack	years	10	12	8	Own assumption
Stationary storage	years	20	25	15	Own assumption
Photovoltaics	years	20	-	-	Own assumption

Table 11 Assumed cost-structure of stationary storage in 2017 (estimated on a kWh-basis) based on BNEF [85]

	Power-designed (¹)	Energy-designed (¹)
Battery pack	42 %	50 %
Inverter	21 %	5 %
Other components	37 %	45 %

(¹) Power-designed battery of C-rate 2 and energy-designed battery of C-rate 0.25.

Table 12 Development of Li-ion EV battery size over time, in kWh

	2017	2025	2030	2035	2040	Source
Passenger BEV	40	52	60	60	60	IRENA [108] (¹)
Passenger PHEV	18	19	20	20	20	Own assumption
Mini electric busses BEV	80	80	80	80	80	Own assumption
Mini electric busses PHEV	30	30	30	30	30	Own assumption
Electric busses BEV	150	150	200	200	200	Own assumption based on [50]
Electric busses PHEV	40	40	40	40	40	Own assumption based on [50]

(¹) IRENA assumes an average of 60 kWh/EV in 2030, here it is assumed constant thereafter.

Learning rates

Table 13 Learning rates of Li-ion battery packs for EVs and of other stationary storage components

	Reference	High	Low	Source
Battery pack	16 %	20 %	12 %	Schmidt et al. [57]
Inverters	19 %	20 %	18 %	IRENA [8]
Other components	12 %	16 %	8 %	Schmidt et al. [57] (¹)
Cell	30 %			Schmidt et al. [57] (¹)

(¹) Assuming learning rate for storage systems.

Annex 4. Results

Table 14 Li-ion battery pack cost trajectories, in €/kWh

	2017	2020	2025	2030	2035	2040
High	200	154	104	75	59	50
Moderate	200	134	96	75	64	56
Low	200	171	127	101	86	75

Table 15 Li-ion stationary storage system cost trajectories (energy-designed, C-rate 0.25), in €/kWh

	2017	2020	2025	2030	2035	2040
High	500	404	294	223	187	164
Moderate	500	393	323	284	233	206
Low	500	443	371	327	273	242

Table 16 Li-ion stationary storage system cost trajectories (power-designed, C-rate 2), in €/kWh

	2017	2020	2025	2030	2035	2040
High	820	663	494	382	323	282
Moderate	820	658	546	481	402	355
Low	820	732	617	546	466	411

Table 17 Li-ion residential stationary storage cost trajectories (C-rate 0.35), in €/kWh

	2017	2020	2025	2030	2035	2040
High	744	601	442	339	285	249
Moderate	744	590	486	427	354	313
Low	744	662	555	489	414	365

Table 18 Range of Li-ion battery costs across all sensitivity and deployment scenarios

	2020	2030	2040
EV battery pack	113 – 178	53 – 121	32 – 98
Energy-designed storage	367 – 459	175 – 406	118 – 279
Power-designed storage	662 – 754	315 – 666	216 – 488

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