Rapidly falling costs of battery packs for electric vehicles

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To properly evaluate the prospects for commercially competitive battery electric vehicles (BEV) one must have accurate information on current and predicted cost of battery packs. The literature reveals that costs are coming down, but with large uncertainties on past, current and future costs of the dominating Li-ion technology[1–3]. This paper presents an original systematic review, analysing over 80 different estimates reported 2007–2014 to systematically trace the costs of Li-ion battery packs for BEV manufacturers. We show that industry-wide cost estimates declined by approximately 14% annually between 2007 and 2014, from above US$1,000 per kWh to around US$410 per kWh, and that the cost of battery packs used by market-leading BEV manufacturers are even lower, at US$300 per kWh, and has declined by 8% annually. Learning rate, the cost reduction following a cumulative doubling of production, is found to be between 6 and 9%, in line with earlier studies on vehicle battery technology[2] . We reveal that the costs of Li-ion battery packs continue to decline and that the costs among market leaders are much lower than previously reported. This

has significant implications for the assumptions used when modelling future energy and transport systems and permits an optimistic outlook for BEVs contributing to low-carbon transport.

The single most important factor in achieving a compelling and affordable mass-market BEV is its relative cost[4]. The key difference in design and cost between BEVs and internal combustion vehicles is the power train—in particular, the battery. It is commonly understood that the cost of battery packs needs to fall to below US$150 per kWh in order for BEVs to become cost-competitive on par with internal combustion vehicles[5]. This paper presents a first- of-its-kind systematic review of the cost of battery packs (in contrast to the cost of constituent cell) to BEV manufacturers of the at present dominating Li-ion technology. Recent noteworthy papers put such costs per kWh in the range €500–1,200 (US$636–1,529; ref. 1) and US$800–US$1,200 (ref. 2) in the 2010–2011 time frame, but these figures stem from only a limited set of data sources. There are also clear signs that costs of batteries are declining: estimates have been published putting costs as high as US$1,000 per kWh in 2012 (ref. 4), citing data from 2008 from the International Energy Agency (IEA; ref. 6) and 2007 from the World Energy Council (WEC; ref. 7). Comparisons between internal combustion and battery electric cars in 2009–2010 found battery costs to be €600(US$764) per kWh (ref. 8) and, most recently, van Noorden reported US$500 per kWh in 2014 in a recent paper[9]. Other recent research[10], as well as major revisions of estimates from key actors studying the industry[11,12], also suggest that costs are declining fast. However, there have been no peer-reviewed studies that systematically review battery pack costs since the introduction of the new generation of BEVs in 2008 (ref. 10).

We review cost estimates of battery packs for BEV application only (high capacity), excluding hybrid vehicle application (high power) as these are typically 30–50% more costly and not used in BEV (ref. 3). We include cost estimates of all variants of Li-ion technology used for BEV, as the aim is to track the progress of BEV technology in general and data is too scarce for individual Li-ion cell chemistry variants. Cost estimates ($N = 85$) included are from peer reviewed papers in international scientific journals; the most cited grey literature, including estimates by agencies, consultancy and industry analysts; news items of individual accounts from industry representatives and experts; and, finally, some further novel estimates for leading BEV manufacturers (see Supplementary Sheet 1). Results are based on $N = 53$ unique estimates (see Methods) and show that average cost, given as $\mu \pm 2\sigma$, for the industry as a whole declined by 14 ± 6% ($N = 53$, $R^2 = 0.28$, $p = 5.1 \times 10^{-5}$) annually from 2007 to 2014 (Fig. 1, blue squares and crosses), and costs for market-leading manufacturers declined by 8 ± 8% ($N = 15$, $R^2 = 0.23$, $p = 0.07$) annually for the same period (Fig. 1, green circles), leading to an estimated current cost range in 2014, given as given as the mean (95% confidence interval for the log model are shown in parentheses), of US$410(250–670) per kWh and US$300(140–620) per kWh respectively. This is of the order of two to four times lower than many recent peer-reviewed papers have suggested. Linear models give similar R^2 values, but an exponential relationship is to be expected[1]. The rates for market leaders is on par with the 6–9% reported by Weiss et al.[1], citing industry analysts[11,13], and 5–8% given by representatives from the industry[14]. We estimate that cumulative battery capacity has grown by more than 100% annually since 2011 (see Supplementary Sheet 3). However, the cost data has too much uncertainty to be used directly together with data on cumulative capacity to estimate learning rates, but using modelled average costs gives a learning rate of 9% ($R^2 = 0.99$, $p = 0.006$) for the industry as a whole and 6% ($R^2 = 0.99$, $p = 0.004$) for market-leading actors (Fig. 2). Finally, results show that costs in 2014 were probably already below average projected costs for the 2020 time frame (Fig. 1, yellow triangles).

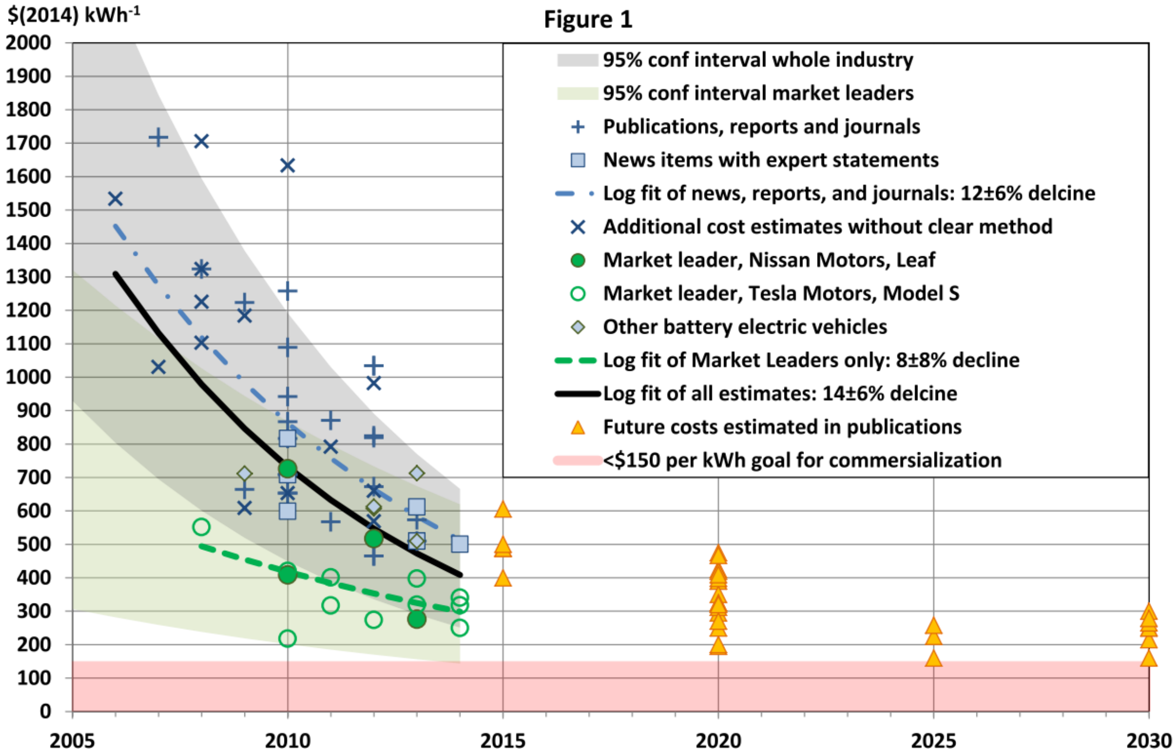

Figure 1. Cost of Li-ion battery packs in BEV. Data are from multiple types of sources and trace both reported cost for the industry and costs for market-leading manufactures. If costs reach US$150 per kWh this is commonly considered as the point of commercialization of BEV.

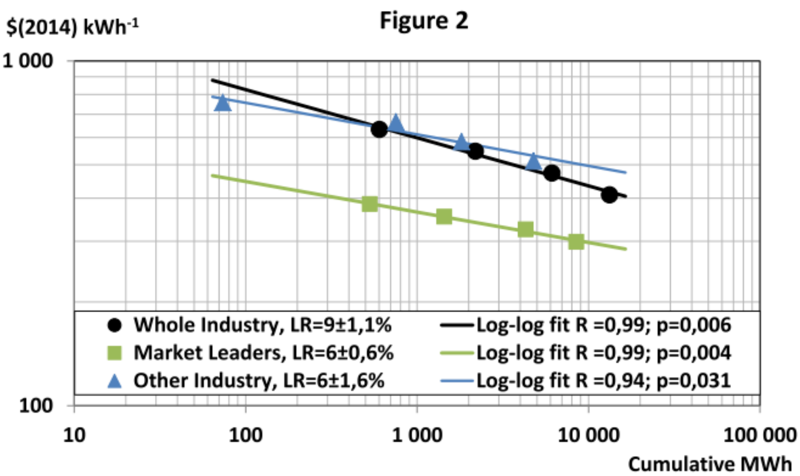

Figure 2. Modelled experience curves for battery packs. Learning rate is based on modelled cost data and estimated cumulative capacity for the whole industry, market leaders, and other industry with market leaders subtracted. Underlying uncertainty in cost data must be taken into account when interpreting results.

The surprisingly steep declines in estimates for the industry as a whole have several possible explanations. They are only partly driven by the inclusion of data on market-leading actors. Removing market-leading actors from the data set gives a $12 \pm 6\%$ decline ($N = 38$, $R^2 = 0.4$, $p = 2.4 \times 10^{-5}$). Cumulative global sales of BEVs are doubling annually, and learning rates for the constituent Li-ion cells have earlier been estimated to be 16–17% (ref. 2). There are still R&D improvements to be made in, for example, anode and cathode materials, separator stability and thickness, and electrolyte composition[3]. Among these factors, input material cost is among the most important, and costs as low as US$300 per kWh due to such improvements have been discussed[2]. Together with improvements due to economies of scale, a 12–14% learning rate is conceivable. A techno-economic explanation for the identified rapid decline in cost is that the period since 2007 represents the earliest stage of sales growth for BEVs. The estimates for the industry as a whole thus reflect a wide range of Li-ion battery variants at initially low production volumes, as well as necessarily immature battery pack production techniques among BEV manufacturers. A rapidly developing and restructuring industry in its early phase could yield high learning rates at pack level. However, the learning rate for NiMH batteries in hybrid vehicle applications have historically been 9% (ref. 2), much closer to the modelled learning rates in this paper. Hence, we believe that the 8% annual cost decline for market-leading actors is more likely to represent the probable future cost improvement for Li-ion battery packs in BEV, whereas the14% decline for the industry as a whole to some degree represents a correction of earlier, overestimated costs. It is likely that the manufacturers with the highest car sales at present will have the most competitive battery pack costs and that these represent a more realistic long-term learning rate. With a cost level of approximately US$300 per kWh these market-leading actors now set the de facto current costs for state-of-the-art battery packs.

It can be expected that the cost gap between market leaders and the industry as a whole will narrow over the coming years. In such a scenario[2], assuming continued sales growth of the order of 100%, and using learning rates and cost declines identified in this paper, there is a convergence of estimates of battery cost for the whole industry and costs for market-leading car manufacturers in 2017–2018 at around US$230 per kWh. This is significantly lower than what is otherwise recognized in peer-reviewed literature, and on par with the most optimistic future estimate among analysts outside academia (by McKinsey), which stated in 2012 that US$200 per kWh can be reached in 2020, and US$160 per kWh in 2025 (ref. 15). From US$230 per kWh, costs need to fall a further third to reach US$150 per kWh, at which BEVs are commonly understood as becoming cost competitive with internal combustion vehicles[5]. More recent academic studies find similar target costs[16], but analysts of, for example, the US market suggest that competitiveness with internal combustion vehicles is reached already at US$400 per kWh for fuel cost of US$6 per gallon, and US$250 per kWh at US$3–4.5 per gallon[11,15], the latter range reflecting current conditions. The International Energy Agency (IEA) estimates that parity with internal combustion cars in general is reached at US$300 per kWh (ref. 17). However, there are large uncertainties in these types of scenarios, and recent empirical research has found no clear correlation between fuel prices and actual BEV uptake[18]. BEV sales are taking off at today's cost of US$300 per kWh, but BEVs are still a niche product among early adopters. As well as lower battery costs, important explanatory factors behind this take-off include public incentive schemes, and the local or regional presence of charging infrastructure and national manufacturers[18], because each of these contribute to alleviating cognitive barriers[10]. However, if costs reach as low as US$150 per kWh this means that electric vehicles will probably move beyond niche applications and begin to penetrate the market widely, leading to a potential paradigm shift in vehicle technology. However, it should be noted that factors such as resource availability and environmental impacts from a life-cycle perspective are also important for the outlook of BEVs, and these are not assessed in this paper.

Our results come with large uncertainties. Variance to mean ratios for individual years seem to be declining ($R^2 = 0.62, p = 0.03$) but sparse data makes statistical testing difficult. The industry is secretive with this sensitive information. It is possible that they overestimate costs to avoid revealing actual costs or, conversely, that they subsidize battery packs to gain market shares. Even though estimates refer to battery packs for full BEV, excluding Li-ion batteries for hybrid electric vehicles, the price range is widened as cost estimates are based on many cell chemistry varieties. Further studies assessing specific cell technologies could give more robust results, but scarce data limited our analysis. Current average cost at US$300 per kWh for market-leading actors in 2014 is, however, very close to key information given by Tesla Motor Chief engineer JB Strubel, who has indicated in 2013 that the costs of the Tesla Model S battery pack is below 25% of the total costs of the car in most cases, corresponding to approximately US$310 per kWh (ref. 19). Similarly, other industry experts[20] have also estimated that battery packs in general make up 25% of vehicle prices, which corresponds to approximately US$300 per kWh, for example, Nissan Leaf in 2014 (see Supplementary Sheet 7).

How likely is it that annual cost reductions of roughly 8% among leading manufacturers can continue? A commercial breakthrough of the next generation of, for example, lithium air-based batteries is still distant[21] and not considered in this paper. Production of BEVs is still in its infancy, but the Li-ion technology was developed in the 1990s and, although further improvements can be expected, many advancements at cell chemistry level have already been realized[22]. Near-term costs are instead driven by cell manufacturing improvements, learning rates for pack integration and capturing increasing economies of scale[2]. The market is at present more than doubling annually and several car manufacturers are investing heavily together with battery manufacturers. Renault–Nissan, together with LG, is aiming for a production capacity enabling the production of 1.5 million vehicles by 2016 (ref. 23) and Tesla Motors, together with Panasonic, have started the construction of a battery plant with a capacity of 0.5 million packs and additional batteries for stationary storage applications (corresponding to 50 GW h per year)[24]. The latter alliance expects more than 30% cost reductions from economies of scale in 2017 compared with 2013 (ref. 25), corresponding to an approximately 7% compound annual decline in costs, a trajectory close to the trends projected in this paper. In fact, it has for some time been projected that large-scale plants will drive down costs to around US$200 per kWh at a production rate of only 100,000 battery packs per year[26,27]. The initiated battery plant investments are at the level of ten times this capacity when fully operational. In conclusion, pending continued strong growth of BEV sales for a few years, it is indeed possible that economies of scale will continue to push cost towards US$200 per kWh in the near future even without further cell chemistry improvements. However, these cost reductions depend on the successful implementation of these large-scale battery production facilities and on continued public support through, for example, economic incentive schemes in key BEV markets.

We show in this paper that costs of Li-ion battery packs to BEV manufacturers continue to decline and that costs are probably much lower than previously reported. Future research efforts for modelling scenarios for energy and transport transitions need to take these lower estimates into account.

Methods

We used data sources in research cited in this paper[1–4,8,10] complemented by a search in Web of Science using search criteria 'TS = (Electric vehicle Li-ion battery cost)' (102 papers, 2014-09-10). The same keywords were used to identify further papers, news items and expert and industry statements by reviewing the first 100 hits retrieved from Google's search engine. We did not include data on costs of battery packs in hybrid vehicles, but sources with estimates stated to be relevant for both types are included. If a given reference did not contain novel data or analysis, data was traced back to its original source. This eliminated cross referrals and duplicate data points (N = 17). For publications and reports we assessed the method used (for example, original analysis of statements from industry, original review, or original analysis of the value chain including material and production cost), and if no method was specified the data was excluded from the review (N = 15; see Supplementary Sheet 1); however, this data is shown for reference as a separate data series in Fig. 1. This analysis was complemented by additional data points from extensive searches for cost estimates for individual car models (five in total identified), and their respective car and battery manufacturers originating from public statements made by company representatives, as well as novel bottom-up calculations based on, for example, reported replacement costs (N = 27; see Supplementary Sheet 1, and 5–13). A total of N = 85 data points were assessed for historical costs and additional data points (N = 37) were identified for future forecast costs (see Supplementary Sheet 1). For all data, cost ranges (if given) were converted with the arithmetic mean of the highest and lowest data points in the range, historical costs were inflation adjusted to US$(2014 as of October 2014) using data from the US Bureau of Labor Statistics (see Supplementary Sheet 3), currencies are converted using historical exchange rates from the US Federal Reserve (see Supplementary Sheet 4). Data was fitted with log regression and 95% confidence intervals derived with a two-tailed t-test. Results are shown as separate regressions for the whole industry, market leaders only, and the net of these two (excluding market leaders) as shown in Fig. 1. We investigated declining uncertainty as change in mean to variance ratio by deriving averages and standard deviations for years 2008–2014 and performing a linear regression of these values. For the calculation of learning rates there were no official sales figures for the global BEV market available, but cumulative battery pack volumes were assessed by combining several sources in press releases for car manufacturers, data provided by actors following the industry[28,29], and data found in individual reports, such as IEA Global EV outlook 2013 (ref. 17). Total 2014 BEV sales is projected based on these sources as final sales were not available at time of submission (October 2014; see Supplementary Sheet 2). Average battery pack sizes for sold cars were assessed based on known properties of market-leading vehicles and an estimated average size of 25 kWh per car for other vehicles (see Supplementary Sheet 2), on par with data used by other papers[2]. Together these sources provided data on cumulative capacity for 2011 through 2014. Learning rates were calculated by regression of log cost data and log cumulative capacity data[1,30]. However, the data on cost contained too high an uncertainty to calculate learning rates directly ($R^2 < 0.1$). Modelled data from this paper for 2011–2014 ($N = 4$) was used instead, which give highly significant results (as shown in Fig. 2), but the underlying uncertainty in cost data must instead be taken into account when interpreting the results. However, as all estimated declines in costs are significant we choose this method to be able to estimate learning rates.

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Author contributions

B.N. conducted the main part of data gathering, review, analysis and writing. M.N. contributed to analysis and writing.

Additional information

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Competing financial interests

The authors declare no competing financial interests