Supplementary information for:

Re-examining rates of lithium-ion battery technology improvement and cost decline

Micah S. Ziegler[†] and Jessika E. Trancik[†,‡,*]

[†]Institute for Data, Systems, and Society, Massachusetts Institute of Technology, Cambridge, MA, USA.

[‡]Santa Fe Institute, Santa Fe, NM, USA.

[*]trancik@mit.edu

January 2021

Contents

1 Additional general methods

1.1 Data extraction from previously published plots

Data collection focused on numerically presented data when available. When data underlying plots were unavailable, values were extracted from plots digitally using WebPlotDigitizer (v 4.1, released January 8, 2018).[1]

1.2 Data series naming convention

When possible, series were named by combining the last name of the primary, original author, collector, or presenter of the data with the year of publication or presentation. If the data are more commonly associated with a certain organization than individual researchers, the name of the organization that collected, presented, or published the data was used instead. If original authorship could not be determined reliably, the author of the publication in which the data were found was employed. Similarly, when sufficient details and references were available, the year was assigned as close as possible to the original reporting or presentation date for a given data series. For example, if a book published in 2005 contained a chart presented at a conference in 2003, the data series name would include 2003. Additional clarifying or distinguishing details are included after the year.

1.3 Plotting

To allow monthly and annual data to be plotted together, annual data are plotted midyear, specifically on July 2^{nd}. Plots displaying a third dimension as a color gradient were generated using functions from the plot3D[2] and colorspace[3] *R* packages.

When co-plotting data with different units (*e.g.* series with price per kWh and price per kWh^2/L), the values were normalized by dividing by the maximum value in the series.

In most cases, slopes provided on plots are independent of the base used when taking the logarithm. This is not the case for equation 1 (Moore's law). In all cases, base 10 was employed.

1.4 Developing projections from previously reported performance curve analyses

Data, lines of best fit, and learning rates were collected from previously reported analyses where the price of lithium-ion cells, in currency units per kWh, was regressed against cumulative installation, production, or sales, in units of energy capacity. (The full set of analyses found in the literature is reported in Table S2.) In Figures 2 and S3–S6, the data are plotted along with simple, extrapolation-based projections. Figures S3 and S5 also present the lines of best fit, extracted from the graphs published in the previous analyses.

When plotting these data and projections based on them, we did not make any assumptions about inflation correction, and the data are plotted as presented by the authors.

Figure 2 contains projections based on the price series alone. For a given price series, a negative exponential growth (decay) curve with time (equation 1, Moore's law) was fit to the data, and the resulting best-fit line was used to project prices from the year following the end of the reported price series through 2050.

Projections based on previous analyses' price and cumulative market size series are presented in Figures S3–S6. These projections differ based on how their future market size series were developed. First, for Figures S3–S4, for a given analysis, the lagged (lag = 1) differences of the cumulative market size series were determined, yielding an annual market size series. Then, an exponential growth model was fit to the annual market size data series (annual market size = AB^x where x is the year), and the model was used to project annual market size from the end of the published data series through 2050. To the latest reported cumulative production value, a cumulative sum of the annual market size projection values was added to yield a cumulative market size projection. For a given analysis plotted in Figures S5–S6, an exponential growth model was fit to the reported cumulative market size series, and the model was used to project cumulative market size from the end of the published data series through 2050. Then, for the projections presented in Figures S3–S6, prices were extrapolated using equation 2 in the main text (Wright's law). For each analysis, these projections started from the latest price and cumulative market size and were developed using the cumulative market size projection and published learning rate. In some cases, this "learning rate" was referred to as an "experience rate" or "price experience factor" and in other cases it was derived from a reported "progress ratio" or "progress rate".

As the plot reported by Shinoda and coworkers[4] was presented with dependent axis units of k¥/kWh, the data for their line of best fit were converted to USD. First, we assumed that the plotted data points corresponded to annual values from 1995 through 2005, which is consistent with their reference to METI's "Machinery Statistic Report, 1993–2005" (their ref. #24). Second, the values for plotted points along the curve were extracted from the plot. Third, independent axis values (*i.e.* the cumulative production values) were regressed against time. An exponential model provided a poor fit (adjusted R^2: 0.8575) so a polynomial fit of degree 2 was employed, using the *lm* and *poly* functions in *R*, resulting in a better fit (adjusted R^2: 0.9972). The resulting model provides an estimate of the relationship between cumulative production values and time employed in their work. Fourth, price and cumulative production values of points along the trend line were extracted, and the polynomial model was used to assign these values to years. Finally, these years were used to obtain appropriate foreign exchange rates to convert the corresponding price data to USD, and the data were converted from Yen to USD using these rates. The resulting price versus cumulative production series reflects the plotted trend line.

1.5 Methods flowchart

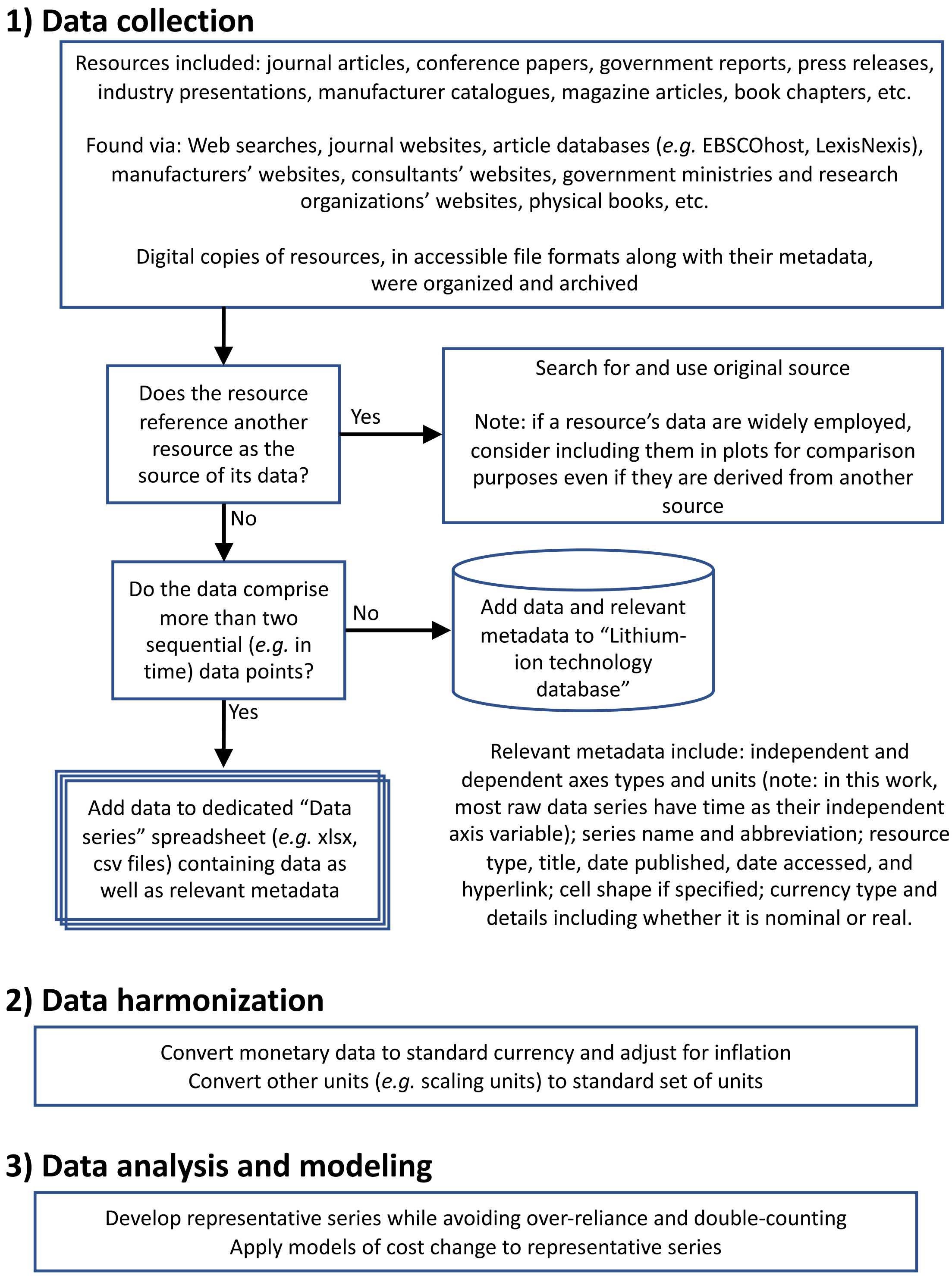


Figure S1: Flowchart summarizing our general data collection, harmonization, and analysis approach.

2 Data collection, preparation, and analysis

2.1 Lithium-ion technology database

Data on battery specifications and prices were collected from a wide variety of sources and compiled into a human- and machine-readable database. Sources include published academic articles, books, government and industry reports, product catalogues and specification sheets, conference proceedings, presentations, magazine articles, and press releases. The database contains 1716 unique records of cells employing lithium-ion and lithium-ion polymer technologies for the years 1990 through 2019. These records were collected from nearly 600 different sources. These records were further classified by a variety of characteristics, including:

1. detail level (*e.g.* cell, module, pack, or system)

2. battery development status (*e.g.* lab, prototype, commercial, etc.)

3. value type (*e.g.* nameplate, measured, estimate, etc.)

4. shape (*e.g.* cylindrical, prismatic, pouch, etc.)

Data describing a given battery were assigned the most relevant year possible, for example, the earliest availability or manufacturing date, if such details were reported. If more relevant dates could not be determined, data were assigned the year of publication or presentation. Data collected from journal articles were assigned the year of submission, if available, or otherwise the date of publication.

When reports provided ranges without specifying a most probable, average, median, or other "central" value, the average of the lower and upper bounds was used.

Our analysis includes cylindrical, prismatic, and pouch cell types; coin cells were excluded. In a few cases, the classification of a record as describing either a prismatic or pouch cell was uncertain so additional information was used to infer cell type. For example, in a few cases, lithium-ion polymer cells were assumed to be pouch cells. Broad estimates of lithium-ion technology's energy density or specific energy, often presented when summarizing or comparing technologies, were also collected but were not employed in most analyses.

Most analyses described herein used the database records that contain nameplate values of commercial cells. Notably, the representative performance metric series were constructed with nameplate values of commercial cells that represented the cells' maximum charge capacities (*e.g.* using charge or energy capacities measured at 0.2 C or ItA for batteries intended to have high energy capacity).

Data collection focused on the two intensive physical properties highlighted in this study: energy density and specific energy. Thus, most database records contain energy density and/or specific energy values, or the data required to derive these values, for individual lithium-ion or lithium-ion polymer cells. The focus on cell-level values avoids the complexity introduced by the diversity of module, pack, and system configurations and components.

When available, database records contain other values, such as: nominal voltage, charging and discharging voltage cutoffs, mass, volume, charge capacity, energy capacity, various measures of peak and continuous power, cycle-life records and estimates, prices, and cell codes. Additional classification details were included when available. For example, when the source was clear, batteries were classified by their intended application (*e.g.* use in portable electronics, high power portable devices, electric vehicles, extreme environments, stationary storage, etc.).

If the original record did not include energy density and/or specific energy values, when possible these were calculated from the energy capacity, volume, and mass of the cell, as given by:

$$\text{energy density}\left(\frac{\text{Wh}}{\text{L}}\right) = \frac{\text{energy capacity}\,(\text{Wh})}{\text{volume}\,(\text{L})} \tag{1}$$

and

$$\text{specific energy}\left(\frac{\text{Wh}}{\text{kg}}\right) = \frac{\text{energy capacity}\,(\text{Wh})}{\text{mass}\,(\text{kg})}. \tag{2}$$

Energy capacity was often estimated from charge capacity and nominal voltage values, using:

$$\text{energy capacity}\,(\text{Wh}) = \text{charge capacity}\,(\text{Ah}) \times \text{nominal voltage}\,(\text{V})\,. \tag{3}$$

Of the nameplate records of commercial lithium-ion cells, approximately 25% of energy density and 35% of specific energy values were obtained directly from the source while 75% of energy density values and 65% of specific energy values were calculated from other reported cell characteristics using the aforementioned formulae. Of the same set of nameplate records, approximately 15% contain energy density and specific energy values both reported directly by the source (*i.e.* the nameplate energy density or specific energy) and calculated from other reported data (*e.g.* charge capacity, voltage, mass, and volume). Comparing the calculated to the directly reported values suggests that calculated values are on average very close to nameplate values (within ca. 1% see Figures S28–S29). This close agreement indicates that calculated and directly reported energy density and specific energy values can be combined without introducing considerable error.

In a few cases, energy density was estimated by multiplying a given specific energy value by the cell's mass and dividing by the cell's volume. Similarly, energy density values could be used to estimate specific energy given reported cell masses and volumes.

Masses and physical dimensions (*e.g.* diameter, height, length, width, thickness, etc.) were sometimes presented as either average or maximum values. When both average and maximum values were available, the maximum volume and mass values were used to calculate energy density and specific energy values, respectively, which might result in a slight underestimate of the derived intensive values. For pouch cells, tabs were excluded from volume measurements.

Similarly, some sources presented different charge or energy capacity values. The higher of the two capacity values was often denoted as "standard", "nominal", or "typical", while the lower was denoted as "rated" or "minimum". When both capacity values were available, the higher of the two was used to calculate energy density or specific energy. Of the records containing calculated energy density values, about 26% had both typical and rated charge capacity values. On average, typical capacities were about 4.5% higher than rated capacities. A comparison between the two classes of capacity values is presented in Figure S30. Sources that only contained values referred to as "rated" or "minimum" were excluded from this analysis. When capacity values were provided at multiple temperatures, the value for the temperature closest to 20–25 °C was employed. When capacity values were provided at multiple discharge rates, the capacity at 0.2 C (or 0.2 ItA) was employed. Energy density, specific energy, and capacity values reported for discharge rates higher than 0.2 C were excluded from this analysis.

For cylindrical cells, when dimensions (*i.e.* diameter and height) were unavailable but an unambiguous cell code (*e.g.* 18650, 21700, etc.) was available, the volume was estimated from the cell code. In the database, about 11% of nameplate energy density values for commercial, cylindrical, lithium-ion cells rely on volumes derived from cell codes. This approach could introduce error as many commercial cylindrical cells slightly exceed the volume defined by their cell code. For example, the prevalence of various nameplate volumes for "18650" cells are plotted in Figure S31, and the difference between these volumes and that defined by the cell code is plotted in Figure S32. As a result, use of volume data derived from cell codes could result in a slight overestimate of calculated energy density values. However, a sensitivity analysis (*vide infra*) suggests inclusion of these data in the development of a representative performance series does not result in a considerable overestimate of energy density values.

Distance matrices were applied to the energy density values in each year to search for possible duplicates. Records with close measures of energy density were identified and their other characteristics compared to determine whether a given record was a simple restatement of another. If a record was found to be a restatement of another record in the same year, the more detailed record was kept in the analysis while the less detailed record was excluded. The same method was applied to identify and exclude duplicate specific energy values.

2.2 Collection, harmonization, and combination of data series

ACDC 2018 Production. Data on Chinese manufacturing output of lithium-ion batteries were obtained *via* the All China Data Center's (ACDC's) China Data Online service in August 2018.[5] Output per month and accumulated annual output through a given month were available for most months from January 2007 through October 2015. The units given for the data were "10000 units." For years where monthly data were available for every month (2007 through 2012), the accumulated totals diverged from the sums of the monthly data, as given in Table S1. For the years, 2013 through 2015, monthly data were not available for all twelve months. Thus, the ACDC 2018 series used in this work comprises the yearly accumulated (*i.e.* December) values for the years 2007 through 2014.

Berenberg 2016 Price per Energy Capacity. In a February 2016 report,[6] Berenberg analysts published

Table S1: Differences in yearly Li-ion battery output data from ACDC (in units of "10000 units")

Year	Yearly sums of monthly output	Accumulated output (December value)	Relative difference (Yearly sums as reference value)
2007	12682	14498	14.3%
2008	92307	103329	11.9%
2009	178515	187517	5.0%
2010	258684	268699	3.9%
2011	294179	296633	0.8%
2012	418507	417850	–0.2%

an annual series of price per energy capacity for the years 2001 through 2015. The prices appear to be specific to "18650 format lithium-ion cylindrical" cells. The data were presented graphically in units of USD per kWh and were assumed to be nominal values. They were extracted and adjusted to 2018 USD as described in the general methods section.

Berenberg 2016 Production. In a February 2016 report,[6] Berenberg analysts published an annual series of global lithium-ion cell production for the years 2001 through 2015. The data were presented graphically in units of GWh. While in context, it was unclear whether this series referred only to the production of 18650-type cells or all cell types, comparison with other data series strongly suggests that this series represents the annual production of all types of lithium-ion cells.

Blomgren 2000 Specific Energy and Energy Density. Annual specific energy and energy density series for 18650-sized cylindrical lithium-ion cells were obtained from a conference paper written by Blomgren for a meeting in January 2000 and published by IEEE.[7] Data were available for the years 1994 through 1999 with yearly resolution. The series were presented graphically and in units of Wh per kg for specific energy and Wh per liter for energy density.

BNEF 2013 Price per Energy Capacity. In a 2013 presentation to the Clean Energy Ministerial,[8] Liebreich of Bloomberg New Energy Finance (BNEF) presented a series of "historic consumer Li-ion battery prices" from 1995 through 2005. While the y-axis is labeled "battery pack" cost, as these values are historic and represent consumer battery prices, they are assumed to be close to cell-level values, in units of USD/kWh. The series was also assumed to comprise nominal prices. The data were presented graphically, and each unlabeled point was taken to represent one year between 1995 and 2005. The data were extracted and adjusted to 2018 USD as described in the general methods section.

BNEF 2013 Production. In the aforementioned 2013 presentation to the Clean Energy Ministerial, Liebreich of BNEF also presented a series of “cumulative production capacity” from 1995 through 2005, with units of MWh. These values were assumed to represent cumulative production of lithium-ion batteries, as measured in energy capacity. They were extracted and subtraction of the previous year’s value from a given year’s value gave annual production values for the years 1996 through 2005.

BNEF 2019 Price per Energy Capacity. In a March 2019 blog post[9] describing their pack-level price series, Goldie-Scot of BNEF included an annual cell-level price per energy capacity series for the years 2013 through 2018. Considering their focus on batteries for transportation applications, this series is classified as representing a combination of cell types. The data were presented graphically and numerically, in units of 2018 USD per kWh.

Brodd 2002 Capacity per Cell. In a conference paper presented in May 2002,[10] Brodd included a nearly annual series of lithium-ion cell capacity for ICR18650 cells, for the year 1991 and years 1994 through 2002. The values were presented graphically in units of Ah.

Brodd 2002 Production: Cells. In the aforementioned conference paper,[10] Brodd included an annual series of lithium-ion cell production, for the years 1993 through 2000. The values were presented graphically, in units of millions of cells. No clear reference was made to a specific cell shape, so the series was categorized as non-specific.

Broussely 2003 Specific Energy and Energy Density. Annual specific energy and energy density series for “low-power–high-energy design” lithium-ion cells were obtained from a conference paper written by Broussely and Archdale for a symposium in September 2003 and published in the *Journal of Power Sources*.[11] Neither the figure nor surrounding text specified a cell size or shape. Data were available for the years 1991 through 2002 with yearly resolution. The projections from 2003 through 2012 were not included in this analysis. The series were presented graphically and in units of Wh per kg for specific energy and Wh per liter for energy density.

Cairn ERA 2016 Cost per Energy Capacity. Deutsche Bank published a report in 2016 that contains a cost series for lithium-ion technologies, including an “energy cell average” in units of USD per kWh.[12] The report cites “Cairn ERA Advisors” as the source of these data, which are provided graphically and numerically. While annual data were provided for 2010 through 2020, the data for 2016 through 2020 were assumed to be projections and thus excluded from this analysis. The remaining values were assumed to be nominal and were adjusted to 2018 USD.

Cao 2015 Production. In a book chapter, Cao and coauthors published a chart of lithium-ion battery production in China from 2010 through 2013.[13] The data were presented graphically with annual resolution and in units of billions of batteries.

China 2018 Production. The data that were available in both the ACDC and NBSC series (March through October 2015) were nearly identical (<0.001% relative difference), strongly suggesting that they measure the same quantity. The yearly accumulated output data from both series were combined to give a series that extends from 2007 through 2017. All values were divided by 100 to give values in "millions of units".

Citi 2015 Price per Energy Capacity. Citigroup published a series of historical consumer lithium-ion battery prices derived from Japanese METI statistics.[14] The annual series covers the years 1995 through 2011 and assumed a conversion rate of 100 Japanese Yen per USD. The prices, in USD per kWh, were assumed in this study to be nominal and thus were adjusted to 2018 USD.

Google Patents (all). Google's public patents data[15] (updated as of March 6, 2019), were parsed using Google's BigQuery[16] web service, to extract all records (patent publications) labeled with the International Patent Classification (IPC) symbol "H01M 10/0525", which corresponds to "Rocking-chair batteries, *i.e.* batteries with lithium insertion or intercalation in both electrodes; Lithium-ion batteries."[17] The entries' filing, publication, and grant dates, as well as their application numbers, family IDs, country codes, application kinds, assignees, and localized titles were then sorted by ascending filing date and exported to a csv file using Google's Data Studio tool.[18] The records (39,755) were grouped into simple families (using the "family_id" field) and included patents (34,778 simple families), translations (39), utilities (3,806), and PCTs (1,132). The number of patent families filed in each year was counted to yield an annual series. If a family contained entries filed in multiple years, the earliest filing date was employed. Non-granted patent applications were not excluded from these sums.

Google Patents (granted). This series comprises the data described in the Google Patents (all) but limited to those entries for which a patent has been granted ("grant_date" not equal to 0). The resulting entries were similarly grouped by simple patent family and the numbers per year, based on earliest filing date, were counted.

IIT 2007 Demand: Cells: Cylindrical, Prismatic, Pouch, and All Types. In a 2007 report,[19] the Institute of Information Technology (IIT) published plots and tables containing both annual records (1996 through 2006) and projections (2007 through 2016) of lithium-ion battery market volume by cell type (cylindrical, prismatic, laminate (or "pouch") cells, and HEV cells) as well as a sum for all types of cells. Data for cylindrical, prismatic, and laminate cells were available for all 11 years, while HEV cells were not included until 2006. Values were obtained from the tables for the years 1996 through 2006. The values are more specifically labeled as "Cell demand" in units of millions of cells per calendar year. Additional plots in the report's next section ("Chapter 1 LIB Market Bulletin 07Q1") suggest that shipment and demand values (measured in millions of cells per month) are very similar, at least for 18650 cells over the course of 2006.

IIT 2007 Price per Energy Capacity: 2.0 to 2.8 Ah. In the aforementioned 2007 report, IIT published a set of bare cell prices, in USD/cell, for 18650 cylindrical cells with average cell capacities of 2.0, 2.2, 2.4, 2.6, and 2.8 Ah.[19] Values were reported graphically for quarters from 2004-Q1 through 2006-Q4. Data for capacities of 2.0, 2.2, and 2.4 Ah were presented for all twelve quarters. For 2.6 Ah cells, data were presented only for 2005-Q3 onward and for 2.8 Ah cells only for 2006-Q2 onward. The values of charge capacity (units: Ah per cell) were multiplied by an average cell voltage of 3.65 V to obtain values of energy capacity (units: Wh per cell). The prices series values were then divided by their respective energy capacities per cell to yield series of prices per energy capacity (units: USD per Wh). The values were multiplied by 1000 to convert them to USD per kWh. The prices were assumed to be nominal and were adjusted to 2018-Q2 USD.

IIT 2007 Shipment: Cells, Value: Cylindrical and Prismatic, Pouch, and All. In the same 2007 report, IIT published charts and tables of secondary cell shipment numbers (units: millions of cells per year) and value (units: billions of Yen per year).[19] Both series were annual, separated the data for cylindrical and prismatic from those for laminate cells, and were presented numerically and graphically. Data for cylindrical and prismatic batteries were presented for the years 1992 through 2007 while laminate batteries data were presented for 1997 through 2007. The sum of both cell shipment data series provided a series for the number of all cells shipped. Another table provided the total shipment of lithium-ion cells (units: millions of cells per year) for the years 2000 through 2007, confirming the summed values. Similarly, the two series of value data were summed to provide a series for shipment value of all lithium-ion cells. The values for 2007 were projected and excluded from this analysis. The currency-valued series were converted from Yen to USD and adjusted to 2018 USD, as described in the general methods section.

IIT 2011 Shipment: Cells: Cylindrical, Prismatic, Pouch, All Types. In a 2016 report,[20] Horn presented a figure showing shipment values for every calendar quarter from 2002 through 2012. The values are presented graphically; for cylindrical, prismatic, and pouch cells; and with units of millions of cells per month. The graph is "based on data from IIT reports" that appear to include reports from 2004 and 2011. Thus, data between 2002 and 2010 are taken as records while values for 2011 and 2012 are assumed to be projections and excluded from this analysis. The monthly shipment values (one for each quarter) were multiplied by three (for the three months per quarter) and summed for each year to yield annual shipment values for cylindrical, prismatic, and pouch cells. The resulting three series were summed in each year to give an annual shipment series for all cell types.

IIT 2012 Production. In a 2014 book chapter, annual production data were reproduced from an IIT report titled: IIT LIB-related Study Program 11–12 and dated February 2012.[21] The data are the total number of lithium-ion cells produced globally per year for the years 2008 through 2011 (units: millions of cells per year).

Ikoma 2006 Energy Density. In a 2006 article in the Matsushita Technical Journal,[22] Ikoma published a plot of energy density for small lithium-ion batteries (figure title: “当社の小型二次電池のエネルギー密度の推移”) for most years between 1993 and 2006. The values were presented graphically and in numerical labels on the plot and given in units of Wh per liter. Based on the article, caption, and range of values, this series was assumed to track cell-level energy density values. However, the plot and associated text does not appear to specify cell shape and so these data are categorized as non-specific.

JPN-KOR-CHN Production, Cells. The METI, KOSIS, and Chinese (ACDC and NBSC) annual production data for the years 2007 through 2017 were summed to give another annual series (JPN-KOR-CHN), as shown in Figure S7. The values in the component series were assumed to refer to cells or single-cell packs. If our assumption is incorrect, or only applicable to some of the data, the resulting series will underestimate the total number of cells produced in a given year. Notably, for the years 2008 through 2016, the values in this series are consistent with those obtained from other sources. From 2012 onward, the values in this series are higher than those found in other sources.

Kittner 2017: Price per Energy Capacity, Production, Patents. These series are available as supplementary information for an article published in mid-2017 by Kittner, Lill, and Kammen.[23] All three series are annual. The price and production series are cell level, specifically for “lithium-ion consumer cells.” The price and production (output) series cover the years 1991 through 2015 while patent data extend from 1986 through 2015. The production series was presented in units of MWh per year. For the price series, the nominal prices, in units of USD per kWh, were employed in this study and independently adjusted to 2018 USD.

Kanamura 2017 Energy Density. An annual energy density series for 18650-sized cylindrical lithium-ion cells was obtained from a book chapter written by Kanamura and published in 2017.[24] The data were available for the years 1992 through 2010 with yearly resolution. The series was presented graphically and in units of Wh per liter.

Kinoshita 2009 Specific Energy and Energy Density. In a presentation dated 2009, Kinoshita of Sanyo Electric Company presented a plot of “gravimetric energy density” (units: Wh/kg) and “volumetric energy density” (units: Wh/l) for cylindrical lithium-ion batteries for most years between 1994 and 2008.[25] The data were extracted using the centers of the plot’s ellipses as data points. The slide notes that the energy density values were calculated using the minimum capacity value.

KOSIS 2018 Production and Shipment, in Packs. Data on the production and shipment of lithium-ion cells in Korea were obtained from the Korean Statistical Information Service (KOSIS).[26] As of August 2018, KOSIS provided production and shipment data for “lithium secondary battery pack” in units of thousands from January 2005 through December 2017 with monthly resolution. This series was summed for each year from 2005 to 2017, yielding an annual time series. All values were divided by 1000 to convert to units of "millions of packs".

Mayer 2012 Patents. In a 2012 article,[27] Mayer *et al.* published a series of cumulative patents published. The annual series was presented tabularly and extended from 1985 through 2005. Subtraction of the previous year's value from a given year's value yielded an annual patent publication series from 1986 through 2005.

Matteson 2015 Production: Energy. Matteson and Williams published a cumulative production series for lithium-ion batteries.[28] The source they cite is a website, which as of March 2019 does not appear to contain the data Matteson and Williams reference. Thus, the series is attributed to them. The data are presented tabularly for every year from 1993 through 2005 in units of GWh. The cumulative production data were converted to an annual production series for 1994 through 2005 by subtracting the previous year's cumulative production value from a given year's value. The values were also converted to MWh.

METI 2019 Production and Shipment, in Cells, Wh, and Value. Data on the production of lithium-ion cells in Japan were obtained from the Japanese Ministry of Economy, Trade and Industry (METI) annual Yearbooks of Machinery Statistics.[29–52] As of May 2019, METI's annual reports contained tables of monthly and yearly statistics on Japanese lithium-ion battery production for "small sized sealed lithium ion rechargeable batteries", from January 1995 through December 2018. From January 2012 on, these reports also collected analogous statistics for "small sized sealed lithium ion rechargeable batteries for automobiles" and "other small sized sealed lithium ion rechargeable batteries." The statistics included production quantities, measured in: 1) number of batteries, units of thousands; 2) battery capacity, in units of thousands of amperehours; and 3) amount of money, in units of millions of Yen. Shipment quantities were also available in the same three measures. The "number of batteries" values were assumed to refer to the number of cells while the "amount of money" values were assumed to represent sales value.

The capacity values were converted from Ah to Wh by multiplying by the nominal operating voltage for lithium-ion cells. The voltage values employed were time-dependent as improvement in lithium-ion technology has led to higher voltages (Figure S33). Using our aforementioned database of lithium-ion battery technologies as a guide, capacity values through December 1998 were multiplied by 3.6 V to convert from Ah to Wh. Values afterward were multiplied by 3.67 V (the average for all cells in the database for the years between 1999 and 2018). The timing of this transition to a higher voltage is consistent with industry reports.[25]

Comparison of reports from different years strongly suggested that the values measured in Yen were nominal. These values were converted to USD and then inflation adjusted as described in the general methods section.

METI 2019 (No Auto) Production and Shipment, in Cells, Wh, and Value. These data series are derived from the METI 2019 series. To remove the impact of including "small sized sealed lithium ion rechargeable batteries for automobiles" in later data, the values between January 1995 and December 2011 were taken from the series for "small sized sealed lithium ion rechargeable batteries" and values from January 2012 through December 2018 were taken from the series for "other small sized sealed lithium ion rechargeable batteries".

METI 2019 (Auto Only) Production and Shipment, in Cells, Wh, and Value. These data series are obtained from the METI 2019 series using only the data in the "small sized sealed lithium ion rechargeable batteries for automobiles" category.

METI 2019 Price per Energy Capacity. To develop a price per energy capacity series, the nominal, unadjusted METI 2019 production value series was divided by the METI 2019 production capacity series in Wh and converted from Wh to kWh. The resulting price per energy series, in units of nominal Yen per kWh was converted to nominal USD and inflation adjusted as described in the general methods section. This was performed for both the monthly and annual data.

METI 2019 (No Auto) Price per Energy Capacity. This series was developed in the same manner as the METI 2019 price per energy capacity series, except that it was derived from analogous METI 2019 (No Auto) production value and energy capacity series.

METI 2019 (Auto Only) Price per Energy Capacity. This series was developed in the same manner as the METI 2019 price per energy capacity series, except that it was derived from analogous METI 2019 (Auto Only) production value and energy capacity series.

Morrison 2002 Energy Density: Cylindrical, Prismatic, and Pouch. In an article published in 2002,[53] Morrison included a figure containing energy density series for cylindrical, prismatic, and "polymer-style" batteries. Based on the article's text, the "polymer-style" series very likely describes pouch cells. The plot contains a mix of historical, present, and projected energy density estimates for the years between 1991 and 2003 and with units of Wh per liter. The historical and current values are included in this analysis while the projections are excluded.

NBSC 2018 Production. Data on Chinese output of lithium-ion batteries were obtained from the National Bureau of Statistics of China in August 2018 and updated with additional data acquired in December 2018.[54] Output per month and accumulated annual output through a given month were available for most months from February 2015 through October 2018. The units given for the data were "10000 units." No year examined had data for all twelve months. Thus the production series used in this work comprises the yearly accumulated (*i.e.* December) values for the years 2015 through 2017.

Osaka 1997 Production Value. In published notes from a panel discussion,[55] Osaka included revenues from the sale of secondary lithium-ion batteries in Japan for the years from 1992 through 1995 with annual resolution. The data were presented graphically and in units of hundreds of millions of Yen. Due to low vertical resolution, the value for 1992 could not be easily distinguished from zero and was excluded. The values were assumed to be nominal and were converted to USD and inflation adjusted to 2018 USD as described in the general methods section.

PatSnap Patents (all). PatSnap's database[56] (updated as of April 24, 2019) was parsed to extract all records labeled with the IPC symbol "H01M 10/0525",[17] and the results (84,269 total) were limited to one representative per simple family (44,904 families). For each year, based on the entries' application dates, the numbers of applications (26,656), patents (14,242), and utilities (4006) were summed.

PatSnap Patents (granted). The parsing and analysis used to obtain the PatSnap Patents (all) series was employed, but the data were limited to the "patents" and "utilities" types, excluding "applications."

Pillot 2015 Sales: Cells, Energy, Value. Annual series of "worldwide" lithium-ion battery sales were obtained from a presentation given by Pillot in March 2015, also available as a PDF.[57] Data were presented graphically for number of cells (units: millions of cells per year), energy (units: MWh per year), and cell-level value (units: millions of dollars per year), all for the years 1995–2015. The data for 2015 were excluded from this analysis as they incorporate a projection. In addition, low vertical resolution led to considerable uncertainty in the first three years of energy capacity values. The data for lithium-ion batteries were extracted and separated from data for nickel cadmium and nickel metal hydride varieties. The sales value data were assumed to reflect nominal prices and were adjusted to 2018 USD.

Pillot 2017 Market Size: Cylindrical, Prismatic, Pouch. Annual series of market size (units: millions of cells per year) were obtained from a presentation given by Pillot in March 2017, also available as a PDF.[58] Separate series were presented for cylindrical (years: 2003–2016), prismatic (years: 2005–2016), and pouch cells (years: 2005–2015). All series were presented graphically, and do not specifically mention whether the data correspond to production, sales, or shipment volumes. Thus, the data are assumed to generally represent the size of the market. Summing these three series gives values very similar (within 3%) to those in the Pillot 2017 sales series (measured in cells). The cylindrical market size series employed here incorporates data from Pillot's "cylindrical cells" series for the years 2003 through 2006, inclusive, and the "18650 cells" series, which had very similar but slightly higher values, for the years 2007 through 2016, inclusive.

Pillot 2017 Market Size: Cylindrical and Prismatic. An annual series of market size for cylindrical and prismatic cells for the years 2005 through 2016 was obtained by summing the separate Pillot 2017 market size series for cylindrical and prismatic cells. Its units are millions of cells per year.

Pillot 2017 Market Size: All. An annual series of market size for cylindrical, prismatic, and pouch cells for the years 2005 through 2015 was obtained by summing the separate Pillot 2017 market size series for the three cell types. Its units are millions of cells per year.

Pillot 2017 Price per Energy Capacity: Cylindrical, Prismatic, Pouch. Annual price series for "cylindrical," "prismatic," and "laminate" lithium-ion battery cells were also obtained from a presentation given by Pillot in March 2017.[58] Data were available for the time between 2005 and 2016, with yearly resolution. The series of average cell prices were presented graphically and in units of dollars per Wh. The prices were assumed to be nominal and were adjusted to 2018 USD.

Pillot 2017 Sales: Cells, Energy, Value. Annual series of "worldwide" lithium-ion battery sales were also presented by Pillot in March 2017.[58] Data were presented graphically for number of cells (units: millions of cells per year), energy (units: MWh per year), and cell-level value (units: millions of dollars per year). Data for number of cells and energy were available for the years 1995 through 2016. However, low vertical resolution led to considerable uncertainty in the first three years of energy capacity values. Data for monetary values were available for the years 2000 through 2016. The data for lithium-ion batteries were extracted and separated from data for nickel cadmium and nickel metal hydride varieties. The monetary sales value data were assumed to reflect nominal prices and were adjusted to 2018 USD.

Pillot 2015–17 Price per Energy Capacity. The Pillot 2015 and 2017 cell-level sales values were assumed to reflect a sum of cell prices. Non-inflation adjusted Pillot 2015 value data (in millions of dollars per year) for the years 1995 through 2014 were divided by the corresponding energy values (in millions of Wh per year) and multiplied by 1000 to give a price per energy capacity series (in nominal dollars per kWh). The same process was applied to Pillot 2017 value and energy series. The two series were then combined, taking the values for 1995 through 1999 from the 2015 data series and the values for 2000 through 2016 from the 2017 data series. Where the two series overlapped (the years 2000 through 2014), their percent difference for each year was equal to or below 6%. The synthesized data series was then converted to 2018 USD. Note that uncertainty in the first few values of this series results from the low vertical resolution encountered in the presented plots of sales as measured in energy capacity over time.

Pillot 2015–17 Price per Cell. This series was synthesized in a manner analogous to that for the Pillot 2015–17 price per energy capacity series, except the sales values were divided by the contemporaneous sales volumes (in millions of cells per year) and the multiplication by 1000 was omitted. The resulting series gave price per cell (in nominal dollars per cell) annually for the years from 1995 through 2016.

Powers 2002 Sales: Cells, Value. In a book chapter published in 2003,[59] MacArthur included data extracted from Powers Reports. These data were presented tabularly and included series of worldwide annual sales of lithium-ion batteries for every other year from 1994 through 2002 in units of millions of cells per year and millions of dollars per year. Values for 2002 were likely projections and thus excluded from this analysis. The currency-valued series was reported in 2000 USD and in this study was adjusted to 2018 USD.

Powers 2002 Specific Energy and Energy Density. In the aforementioned book chapter,[59] MacArthur also published specific energy and energy density data extracted from Powers Reports. These data were presented tabularly and included series of lithium-ion cells' specific energy (units: Wh/kg) and energy density (units: Wh/l) for every other year between 1992 and 2002.

Takeshita 1998 Production: Cells, Energy; and Sales Value. Annual series of worldwide lithium-ion, nickel metal hydride, and nickel cadmium cell production, measured in number of cells (units: millions of cells per year) and energy capacity (units: MWh per year), as well as the sales value of these portable cells were reproduced in a 1999 article by Broussely, Biensan, and Simon.[60] The authors cite a Nomura Research Institute report, published by H. Takeshita in 1998, as their data source. All three data series cover 1993 to 1999 and are reported graphically with annual resolution. As the 1999 values are projections, they have been excluded from this analysis. In addition, the lithium-ion cells and energy production values for 1993 and the cells production value for 1994 were too small to reliably extract from the plot. The value series, reported in millions of dollars per year, is assumed to comprise nominal values and was adjusted to 2018 USD.

Takeshita 1998 Production: Cells: Cylindrical, Prismatic. In the same article,[60] Broussely, Biensan, and Simon also reproduced a figure summarizing the "evolution of Li ion cell type", which graphically displays the percentage of cells that are either cylindrical or prismatic. The annual data are presented for 1993 through 1997 in units of "Number of cells, %". The percentage values were extracted, and for the years 1995–1997, were multiplied by the cell production values obtained from an earlier figure. (For the years 1993 and 1994, production values, as measured in number of cells, were too small to reliably extract from the earlier plot.) The resulting series present the number of cylindrical and prismatic cells produced annually from 1995 through 1997, in units of millions of cells.

Takeshita 1998 Price per Energy Capacity. This series was synthesized by dividing the non-inflation-adjusted Takeshita 1998 sales value series (in millions of USD per year) by the Takeshita 1998 production series (energy, measured in MWh per year) and multiplying by 1000 to obtain a series in units of USD/kWh. This process assumes that sales and production series are similar for the years 1994 through 1998, which is supported by the Japanese METI data. The resulting price per energy capacity series was then adjusted to 2018 USD.

Takeshita 1998 Price per Cell. This series was synthesized in the same manner as the Takeshita 1998 price per energy capacity series, except the divisor was the Takeshita 1998 production series (measured in millions of cells) and no multiplication by 1000 was required.

Takeshita 2001 Shipment: Cells. In a presentation dated October 1, 2001, Takeshita, then the Vice President of the Institute of Information Technology, presented a series of worldwide lithium-ion cell shipment values from 1996 through 2001.[61] A copy of the presentation was provided by David Morrison. The series is presented graphically, has quarterly resolution, and excludes "polymer" cells, which are displayed separately. The values are presented in units of millions of cells per month. The quarterly values for a given year were summed, and the sums multiplied by three to give an annual series of cell shipment numbers per year for each year from 1996 through 2001.

Takeshita 2003 Price per Energy Capacity. In a 2005 book,[62] Pistoia included a plot of various battery price series obtained from a presentation by Takeshita at the 20th International Seminar on Primary/Secondary Batteries in Fort Lauderdale, Florida in March 2003. The plot contains an annual series of the "average prices of Li-ion (including polymer-types)" extending from 1995 through 2002. This series was assumed to refer to cell-level prices. The data were extracted from the plot and multiplied by 1000 to convert them to USD per kWh. The prices were assumed to be nominal and were adjusted to 2018 USD.

Takeshita 2004 Price per Energy Capacity: 1.8 to 2.4 Ah. In the aforementioned book,[62] Pistoia also included a plot of bare-cell price series obtained from a presentation by Takeshita at the 21st International Seminar on Primary/Secondary Batteries in Fort Lauderdale, Florida in March 2004. The plot contains series of 18650 bare-cell prices, in units of USD per cell, for cells with capacities of 1.8, 2.0, 2.2, and 2.4 Ah. The series contained prices for every other quarter extending from the fourth quarter of 2000 through the fourth quarter of 2004. The quarters were assumed to refer to calendar-year quarters. The data were extracted from the plot, divided by the product of the cell charge capacity and 3.65 V to scale by energy capacity in units of Wh, and then multiplied by 1000 to convert the values to USD per kWh. The prices were assumed to be nominal and were adjusted to 2018 USD.

Takeshita 2006 Energy Density. An annual energy density series for 18650-sized cylindrical lithium-ion cells was obtained from slides prepared by Takeshita (dated 2006-04) and published online by Japan's METI.[63] Data were available for 1991 through 2006, with yearly resolution. The series was presented tabularly and graphically, both in units of Wh per L.

Takeshita 2006 Price per Energy Capacity. An annual price series for 18650-sized cylindrical lithium-ion cells was obtained from the aforementioned slides prepared by Takeshita.[63] Data were available for 1991 through 2006, with yearly resolution. The series of prices, presented tabularly and graphically in units of Yen per Wh, were assumed to be nominal values. They were extracted, converted from Yen to USD, and adjusted to 2018 USD as described in the general methods section.

Takeshita 2006 Specific Energy. An annual specific energy series for 18650-sized cylindrical lithium-ion cells was also obtained from the aforementioned slides prepared by Takeshita.[63] Data were available for 1991 through 2006, with yearly resolution. The series was presented tabularly and graphically, both in units of Wh per kg.

Takeshita 2007 Sales: Cylindrical and Prismatic, Pouch, All. In a presentation dated March 29, 2007, Takeshita presented an annual series of the sales of portable secondary batteries by type.[64] Cylindrical and prismatic lithium-ion batteries were grouped together and separated from laminate lithium-ion batteries. Sales values were presented numerically and graphically. Data for cylindrical and prismatic batteries were presented for the years 1991 through 2007 while laminate batteries data were presented for 1998 through 2007. These series were summed to give an additional series for sales of all types of lithium-ion batteries. The values for 2007 were assumed to be projections and excluded from this analysis. The values were presented in units of millions of USD per year, and assumed to be nominal and thus were adjusted to 2018 USD.

Thackeray 2004 Production. In a 1999 article, Thackeray reported figures for the annual production of lithium-ion cells for 1996 and 1997 (units: millions of cells per year).[65]

TIAX 2002 Cylindrical and Prismatic Specific Energy and Energy Density. In their 2003 report, Srinivasan and Lipp reproduced plots of “gravimetric vs. volumetric energy density” for cylindrical (specifically 18650) and prismatic lithium-ion cells.[66] Their source for these data series appears to be TIAX LLC. The series are presented graphically and the corresponding year for each datapoint is provided in a label. The data are annual and cover most years between 1995 and 2002.

TIAX 2005 Production. In a 2005 report, Brodd included a chart of worldwide lithium-ion cell production for the years from 1995 through 2002.[67] The annual data were presented graphically and numerically with units of millions of cells per year.

Yoshino 2014 Energy Density. An annual energy density series for lithium-ion batteries was obtained from a book chapter written by Yoshino and published in 2014.[68] Data were available for the time from 1992 through 2011, with yearly resolution. The series of prices was presented graphically. The data were presented in units of Wh/L and assumed to reflect energy density at the cell-level.

Yoshino 2014 Price per Energy Capacity. An annual price series for “bare cylindrical” 18650-sized lithium-ion cells was obtained from the aforementioned book chapter written by Yoshino.[68] Data were available for the time from 1992 through 2011, with yearly resolution. The series of prices were presented graphically and due to limited vertical resolution, data after the year 2007 were excluded from this analysis. The data were presented in units of Yen per Wh and assumed to be nominal prices. The prices were extracted, converted from Yen to USD, and adjusted to 2018 USD, as described in the general methods section.

Yoshino 2014 Sales. An annual series for “worldwide” sales of lithium-ion batteries was obtained from the same chapter written by Yoshino.[68] Data were available for the time from 1992 through 2011, with yearly resolution. The series of sales amounts was presented graphically. The data were presented in units of 10^3 million Japanese Yen per year and assumed to represent cell-level sales and be nominal values. The data were converted from Yen to USD and adjusted to 2018 USD, as described in the general methods section.

2.3 Development of representative data series

Representative 2019 Price per Energy Capacity, Cylindrical Cells. This series is designed to represent the price of cylindrical lithium-ion cells for the years from 1991 through 2016, with annual resolution. The series is developed from the collected price series and data points and primarily relies on three price per energy capacity series: Takeshita 2006, Yoshino 2014, and Pillot 2017. The combination of these series was validated by a few single-year price estimates collected in the database. Even though most cells manufactured in the early-to-mid 1990s were cylindrical, METI data were not included in the development of this series because by 1995, when the METI data series begins, approximately 25% of cells produced were prismatic.[60]

The value for 1991 was derived in two steps. First, the Yoshino series was extrapolated backward by one year. This was accomplished by calculating the annual ratios of the Yoshino to the Takeshita series for the years 1992 through 1995, which were all between 1.75 and 1.91, and averaging the four ratios. This average ratio was then multiplied by the Takeshita value for 1991 to estimate a Yoshino series value for 1991. Second, this estimated value and the Takeshita value for 1991 were averaged to provide the representative value for 1991. For the years 1992 through 2004, this series comprises the averages of the annual values reported by Takeshita and Yoshino. For 2005, the average value from all three aforementioned series is used. For 2006, the average of the Takeshita and Pillot values is used. For 2007 through 2016, the Pillot series values are employed.

Representative 2019 Price per Energy Capacity, All Cell Types. This series is designed to represent the price of all types of lithium-ion cells for the years from 1991 through 2018, with annual resolution. The series is developed from the collected price series and data points and primarily relies on six price per energy capacity series: the representative series for cylindrical cells, Takeshita 1998, Takeshita 2003, Pillot 2015–17, BNEF 2019, and METI 2019 (all data, annual). The combination of these series was validated by a few single-year price estimates collected in the database.

The first three data points in this series (1991 through 1993, inclusive) are obtained from the representative series for cylindrical cells because before 1994, nearly all commercially produced lithium-ion cells were cylindrical.[60] The price per energy capacity for 1994 is from the Takeshita 1998 series. For the years 1995 through 1998, the representative series is the average of the Takeshita 1998, Takeshita 2003, and METI 2019 annual series. In 1999, the average of the Takeshita 2003 and METI 2019 series is used. For 2000 through 2002, the Takeshita 2003, Pillot 2015–17, and METI 2019 series are averaged. For 2003 through 2012, the Pillot 2015–17 and METI 2019 series are averaged. For 2013 through 2016, the Pillot 2015–17, BNEF 2019, and METI 2019 series are averaged. Finally, for 2017 and 2018, the BNEF 2019 and METI 2019 series are averaged.

While the Pillot 2015–17 series contained data for the years 1995 through 1999, these data are considered suspect. As described above, the Pillot 2015–17 price per energy capacity series was derived from market value and market size series. The Pillot 2015 and 2017 market size estimates (in energy capacity, MWh) are considerably lower than the values provided by all other sources, including those in METI 2019 (see Figure 4), which results in very high values for price per energy capacity. Considering the reliability of the METI data and the close agreement of the remaining series, the prices derived from the Pillot 2015 and 2017 market size series were excluded from the averages that compose this representative series for the years prior to 2000.

Representative 2019 Market Size, Cylindrical Cells. This series is designed to represent the market size for cylindrical lithium-ion cells for the years 1992 through 2016, with annual resolution. This series primarily relies on four cylindrical cell–specific data series: Takeshita 1998 Production, IIT 2007 Demand, IIT 2011 Shipment, and Pillot 2017 Market Size. This series also relies on a series of cylindrical and prismatic market size values (IIT 2007 shipment) as well as a plot of the percentage of cells that are either cylindrical or prismatic for the years from 1993 through 1997, as reproduced by Broussely, Biensan, and Simon.[60] The percentages plot indicates that 100% of the lithium-ion cells manufactured in 1993 were cylindrical. Thus, a value of 100% was also employed for 1992. The resulting series of cylindrical cell percentages was multiplied by the IIT 2007 shipment values for cylindrical and prismatic cells combined, for the years 1992 through 1997. The result is a series of shipment values for cylindrical cells, in units of millions of cells, hereafter referred to as the "derived series".

For the years 1992, 1993, and 1994, the derived series provides the only cylindrical-specific market size estimates available, and these are used directly in the representative series. For 1995, the derived series value is averaged with that obtained from the Takeshita 1998 Production series. For 1996 and 1997, the derived series values are averaged with those from Takeshita 1998 Production and IIT 2007 Demand series. For 1998 through 2001, the only data available are from the IIT 2007 Demand series, and these are used directly in the representative series. For 2002 through 2006, the IIT 2007 Demand and IIT 2011 Shipment series are nearly identical (less than 1% difference for each year). For 2002, the average of these two values was used in the representative series. To avoid overreliance on data from IIT, for the years 2003 through 2006, the two IIT series are averaged and the resulting values are averaged with the Pillot 2017 Market Size series. For the years 2007 through 2010, the representative series uses the average of the Pillot 2017 Market Size and IIT 2011 Shipment series. Finally, for the years 2011 through 2016, the representative series uses the values from the Pillot 2017 series.

Representative 2019 Market Size, Cylindrical and Prismatic cells. This series is designed to represent the market size for cylindrical and prismatic lithium-ion cells for the years 1992 through 2016, with annual resolution. This series primarily relies on three data series: IIT 2007 shipment, METI 2019 (no auto), and Pillot 2017 market size for cylindrical and prismatic cells. While data series from METI do not distinguish between cell shapes, histories of lithium-ion technology as well as data presented by Takeshita[64] and IIT[19] strongly suggest that pouch cells did not significantly contribute to worldwide production before 1998. Thus, only the annual METI production values from 1995 through 1997 are employed in this data series. For the years 1992 through 2016, when multiple estimates were available, the maximum "market size" of the individual series is employed in the representative series. For 1992 through 1994, the only available values are those from IIT 2007. For 1995 and 1996, the maximum values are found in the series from METI. For 1997 through 2006, the maximum values are found in the IIT 2007 series. Finally, for 2007 through 2016, the values used are those from the Pillot 2017 series. For the first year switching between series, 1995, the IIT and METI data are nearly identical (31 and 32 million cells, respectively). For the second switching year, 1997, the METI and IIT data are still nearly identical (193 vs 195 million cells, respectively). For 2006, just before the third switch, the IIT and Pillot data are also very similar (1,970 vs 1,865 million cells, respectively).

Representative 2019 Market Size, All Cells. This series is designed to represent the market size for all lithium-ion cell types for the years 1992 through 2017 in units of millions of cells per year. This series relies on seven series that represent market size for all cell types: TIAX 2005 Production, IIT 2007 Shipment (All), IIT 2012 Production, Pillot 2017 Sales (Cells), Pillot 2017 Market Size (All), JPN-KOR-CHN Production (Cells), and METI 2019 (Cells). Production, shipment, and sales values are all taken to approximate "market size" and are combined in this series. METI data, while Japan-only, is used to improve data quality for the 1990s, when Japanese companies produced a vast majority of lithium-ion cells.[19,61,62,69,70] As Japan's METI is considered reliable, series whose 1990s values deviated substantially from METI data are excluded from the development of this representative series. The representative series comprises the maximum value of the seven aforementioned series for each year. Toward the end of the series, the JPN-KOR-CHN series affords the maximum values, consistent with estimates that the vast majority of cells were manufactured in Asia during that period.[21,71–76]

Representative 2019 Market Size, Energy Capacity. This series is designed to represent the market size for all types of lithium-ion cells for the years 1991 through 2016, with annual resolution. This series primarily relies on four data series that measure production or sales in units of energy capacity: Kittner 2017, Takeshita 1998, Pillot 2017, and METI 2019. While METI data series are specific to Japan, before the year 2000, Japan was by far the largest producer of lithium-ion cells[19,61,62,69,70] so the METI data for the years up to and including 1999 are employed in developing this representative series. As Japan's METI is considered reliable, series whose 1990s values deviated substantially from METI data are excluded from the development of this representative series. For years 1991 through 1993, the representative series uses the only reliable data obtained, those from the Kittner 2017 series. For 1994, an average of the Kittner 2017 and Takeshita 1998 values are employed. For 1995 and 1996, the METI 2019 series has the largest production values, and thus these are employed directly in the representative series. For the years 1997 and 1998, the representative series uses the average of the Kittner 2017, Takeshita 1998, and METI 2019 values. For 1999, the representative series is the average of the Kittner 2017 and METI 2019 values. For 2000 through 2015, the Kittner 2017 and Pillot 2017 series values are averaged. For 2016, the representative series draws from only the Pillot 2017 series. The representative series, like the four from which it is derived, has units of MWh.

Representative 2019 Market Value. This series is designed to represent the market value for all types of lithium-ion cells for the years 1991 through 2016, with annual resolution. This series primarily relies on eight data series that measure production, shipment, sales, or market value in currency units: Takeshita 1998 Sales, Powers 2002, Takeshita 2007 Sales, IIT 2007 Shipment, Yoshino 2014, Pillot 2015 Sales, Pillot 2017 Sales, and METI 2019 Production. While METI data series are specific to Japan, before the year 2000, Japan was by far the largest producer of lithium-ion cells[19,61,62,69,70] so the METI data for the years up to and including 1999 are employed in developing this representative series. For each year, the representative series is composed of the average of the aforementioned series' data available for that year. The representative series has units of real 2018 USD.

Representative 2018 Performance Metric Series, Cylindrical. A variety of methods were examined to develop series that appropriately represent the improvement over time in energy density and specific energy for commercially available cylindrical lithium-ion cells. Three approaches were explored to develop yearly values: averages, percentiles, and maxima. In addition, the application of a rule that prevented the value from descending was examined. Possible series are displayed in Figures S18–S19. The annual 98th percentile was chosen to develop the representative series. For both, values employed from the lithium-ion technology database were limited to those records classified as nameplate values for commercial cells. **Energy Density.** This series contains the 98th percentile of energy density (units: Wh per L) of the nameplate data collected for commercial cylindrical cells for each year from 1991 through 2018. The series draws from the values in the Blomgren 2000, Morrison 2002, TIAX 2002 (cylindrical), Takeshita 2006, Kinoshita 2009, and Kanamura 2017 series as well as the database described above. Inclusion of energy density values that rely on volumes estimated from cell codes does not considerably change the resultant series (see Figure S34). **Specific Energy.** This series contains the 98th percentile of specific energy (units: Wh per kg) of the nameplate data collected for commercial cylindrical cells for each year from 1991 through 2018. The series draws from the values in the Blomgren 2000, TIAX 2002 (cylindrical), Takeshita 2006, and Kinoshita 2009 series as well as the aforementioned database.

Representative 2018 Performance Metric Series, All Types. The same methods examined to develop energy density and specific energy performance metric series for cylindrical lithium-ion cells were also applied to data for all cell types. As with the cylindrical cells series, the annual 98th percentile was chosen to develop the representative series. For both, values employed from the lithium-ion technology database were limited to those records classified as nameplate values for commercial cells. **Energy Density.** This series contains the 98th percentile of energy density (units: Wh per L) of the nameplate data collected for commercial cylindrical, prismatic, and pouch cells for each year from 1991 through 2018. The series draws from the values in the Blomgren 2000, Morrison 2002 (cylindrical, prismatic, and pouch), TIAX 2002 (cylindrical and prismatic), Powers 2002, Broussely 2003, Takeshita 2006, Ikoma 2006, Kinoshita 2009, Yoshino 2014, and Kanamura 2017 series as well as the database described above. **Specific Energy.** This series contains the 98th percentile of specific energy (units: Wh per kg) of the nameplate data collected for commercial cylindrical, prismatic, and pouch cells for each year from 1991 through 2018. The series draws from the values in the Blomgren 2000, TIAX 2002 (cylindrical and prismatic), Powers 2002, Broussely 2003, Takeshita 2006, and Kinoshita 2009 series as well as the aforementioned database.

3 Supplementary data tables

Table S2: Phenomenological analyses of lithium-ion technology cost change[a]

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)[b]	Results (as reported)	R^2	Other	Ref.
2009	Electric vehicles	Consumer electronics (tentative)	Cell (tentative)	Cumulatieve afzet (Cumulative sales) (kWh)	Prijs (Price) (dollar/kWh)	1993–2003 (annual)	Log-log linear fit (tentative)	Progress ratio: 83%			[77]
2009	Large-scale energy storage	Small-scale	Cell (tentative)	Total shipment volume (millions of cells per year)	Price (USD/cell)	1997–2003 (annual)	$P(x) = cx^r$	$P = 218.08x^{-0.506}$ Learning rate: 30%		Both datasets based on Japan's MITI (now METI) data	[78]
2009	Electric vehicles	Consumer electronics		Year	Price (USD/Wh)	1998–2005	Compound annual price decrease	9.9%			[79]
2009	Electric vehicles	Consumer electronics		Year	Price (USD/Wh)	2002–2005	Compound annual price decrease	5.4%			[79]
2010	Electric vehicles	Laptops		Year	Price (USD/kWh)	1995, 2009	Compound annual growth rate[c]	CAGR: $\approx -14\%$			[80, 81]
2010	Electric vehicles	Electric vehicles	Pack	Year	Price (USD/kWh)	(predicted)	Compound annual growth rate	CAGR: -7.5%		Predicted growth rate	[80, 81]

continued on next page...

Table S2 – continued from previous page

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)	Results (as reported)	R^2	Other	Ref.
2011	Electric vehicles	"small-size lithium-ion batteries"	Cell (tentative)	Cumulative production (MWh)	Battery cost/price (k¥/kWh)	unclear, likely 1995–2005 (annual)	$P = P_0 \left(\frac{x}{x_0}\right)^{-\beta}$ and $PR = 1 - 2^{\beta}$	"Progress rate": 70%	0.96		[4]
2012	Electric vehicles	High energy consumer	Cell (tentative)	Cumulative sales (MWh)	Price (USD/kWh)	1991–2005 (annual)	$P_n = P_0 x_n^a$ where P_n is the unit cost of the n^{th} unit P_0 is the unit cost of the first unit x_n is cumulative production volume up to the n^{th} unit a is the "degression" parameter	Learning rate: 14%	0.910		[27]

continued on next page...

Table S2 – continued from previous page

Date	**Research context**	**Battery application**	**Level**	**Independent variable(s) (x, y, z)**	**Dependent variable (P)**	**Time period used to fit**	**Functional form (as reported)**	**Results (as reported)**	R^2	**Other**	**Ref.**
2012	Electric vehicles	High energy consumer	Cell (tentative)	Cumulative sales (MWh) and cumulative published patents (number)	Price (USD/kWh)	1991–2005 (annual)	$P_t = P_0 y_{t-x}^b v_t^c$ where P_t is the original unit cost of a unit in period t; P_0 is the unit cost of the first unit; y_{t-x} is cumulative published patents at the end of a period; v_t is cumulative production volume at the end of a period; b is a degression factor of an R&D-based experience effect; c is a degression factor of a general experience effect; t is time; x is a delay period for the effect of technology and LR (cumul. patents) $= 1 - 2^b$; LR (cumul. prod) $= 1 - 2^c$	Learning rate: 8% (“general experience effect”) and 27% (“R&D-based experience effect”)	0.957		[27]
2013	Electric vehicles	Laptop batteries				1997–2012		“laptop batteries developed at a rate of 15%”			[82]
2013	Electric vehicles	Electric vehicles			Cost (USD/kWh)	(projected)	“projected compound annual growth of the learning rate, which describes the reduction in cost of batteries through economies of scale”	“Learning rate”: 9.5%			[82]

continued on next page...

Table S2 – continued from previous page

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)	Results (as reported)	R^2	Other	Ref.
2015	Electric vehicles	Consumer electronics	Cell (tentative)	Cumulative production (GWh)	Price (2005USD/kWh)	1993–2005 (annual)	$P(x) = P_0\left(\frac{x}{x_0}\right)^{-a}$ $LR = 1 - 2^a$ $C(P) = \frac{\$600}{kWh}\left(\frac{P}{2.3e6}\right)^{-\log_2(1-LR)}$	$\log(P(x)) = -0.3536 \times \log(x) + 5.3022$ Learning rate: 22%	0.955		[28]
2015	Electric vehicles	Electric vehicles (whole industry)	Pack	Cumulative capacity (MWh)	Cost (2014USD /kWh)	2011–2014 (annual)	Log–log linear fit	Learning rate: 9±1.1%	0.99 with $p = 0.006$	Modeled cost data were used	[83]
2015	Electric vehicles	Electric vehicles (market leaders)	Pack	Cumulative capacity (MWh)	Cost (2014USD /kWh)	2011–2014 (annual)	Log–log linear fit	Learning rate: 6±0.6%	0.99 with $p = 0.004$	Modeled cost data were used	[83]
2015	Electric vehicles	Electric vehicles (other industry)	Pack	Cumulative capacity (MWh)	Cost (2014USD /kWh)	2011–2014 (annual)	Log–log linear fit	Learning rate: 6±1.6%	0.94 with $p = 0.031$	Modeled cost data were used	[83]
2015	Electric vehicles	Electric vehicles	Pack	Cumulative production (MWh)	Price (2014USD /Wh)	2010–2014 (annual)	Log–log linear fit (tentative)	"m = 21.6%"			[84]
2015	Residential energy storage	Electric vehicles		Cumulative production (MWh)	Cost (€/kWh)		Log–log linear fit (tentative)	Learning rate: 23.2%	0.8973		[85]
2015	Energy storage	"Cellular phone LIB"	Cell	Cumulative LIB capacity (MWh)	Price (USD/kWh)	likely 2000–2013 (annual)	Log–log linear fit (tentative)	PEF: ≈25%		Data from Pillot (2014)	[86]
2015	Energy storage	"Automotive (EV) LIB"	Cell	Cumulative LIB capacity (MWh)	Price (USD/kWh)	likely 2009–2013 (annual)	Log–log linear fit (tentative)	PEF: ≈15%		Data from Pillot (2014)	[86]

continued on next page...

Table S2 – continued from previous page

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)	Results (as reported)	R^2	Other	Ref.
2015	Energy storage	"consumer"		Manufacturing capacity	Cost			"reduction in cost for each doubling of manufacturing capacity": 22%			[87]
2015	Energy storage	Electric vehicles	Pack		Cost (USD/kWh)	2010–2015 (annual)		Learning rate: 15%			[87]
2016	Batteries		Cell	Global lithium-ion cell production (GWh)	Price (USD/kWh)	2001–2015 (annual)	$P = mx + b$	$P = -15.6x + 718$ "Every doubling of cell production has historically led to a 35% reduction in cell prices."	0.89		[6]
2017	Batteries	Electric vehicles and stationary storage	Pack	Capacity	Price		"Price decrease for every doubling of capacity"	Learning rate: 19%			[88]
2017	Electric vehicles and energy storage	"Consumer"	Cell	Annual production (MWh)	Price (2015USD /kWh)	1991–2015 (annual)	$P_t = \delta_0 + \delta_1 x_t + \epsilon_t$ where P_t is logarithmized price and x_t is logarithmized production volumes	"Learning rate of economies of scale": 17.31%	0.9228 (adj.)		[23]
2017	Electric vehicles and energy storage	"Consumer"	Cell	Cumulative production (MWh)	Price (2015USD /kWh)	1991–2015 (annual)	$P_t = \zeta_0 + \zeta_1 y_t + \epsilon_t$ where P_t is logarithmized price and y_t is logarithmized cumulative production volumes until year t	Learning rate "for cumulative production": 15.47%	0.9471 (adj.)		[23]

continued on next page...

Table S2 – continued from previous page

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)	Results (as reported)	R^2	Other	Ref.
2017	Electric vehicles and energy storage	"Consumer"	Cell	Cumulative patents (number filed)	Price (2015USD /kWh)	1991–2015 (annual)	$P_t = \vartheta_0 + \vartheta_1 z_t + \epsilon_t$ where P_t is logarithmized price and z_t is logarithmized cumulative patents until year t	"Learning rate for cumulative patents": 31.43%	0.9861 (adj.)		[23]
2017	Electric vehicles and energy storage	"Consumer"	Cell	Annual production (MWh) and Cumulative patents (number filed)	Price (2015USD /kWh)	1991–2015 (annual)	$P_i = \gamma_0 + \gamma_1 x_i + \gamma_2 z_i + \epsilon_i$ and forecasted price = $\left(\frac{10^{\gamma_0}}{x_i^{-\gamma_1}}\right)(10^{\gamma_2})^{z_i}$ where x_i is logarithmized production volumes and z_i is cumulative patents during each year and P_i is logarithmized price	"Learning rate...for economies of scale (doubling annual production)": 16.9% and "Decrease in prices of 2.0% per 100 PCT patents."	0.9465 (adj.) with $P < 0.001$		[23]
2017	Electric vehicles		Pack	Production capacity of materials (MC), overhead (OH), and labor (L)	Cost of goods sold		$COGS_n =$ $(0.765)^n \times MC_0$ $+(0.757)^n \times OH_0$ $+(0.574)^n \times L_0$ $n = 0$ for the initial conditions in 2015 $n = n + 1$ for each market doubling			Rates were adopted from a study of learning rates in the chemical processing industries[89]	[90]
2017	Energy storage	Electronics	Cell (tentative)	Cumulative production (GWh_{cap})	Price (2015USD /kWh_{cap})	1995–2011 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 30±3%	0.947		[91]

continued on next page...

Table S2 – continued from previous page

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)	Results (as reported)	R^2	Other	Ref.
2017	Energy storage	Electric vehicles	Pack	Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	2010–2016 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 16±4%	0.903		[91]
2017	Energy storage	Residential		Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	2013–2016 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 12±4%	0.954		[91]
2017	Energy storage	Utility	System	Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	2010–2015 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 12±3%	0.924		[91]
2017, 2019	Energy storage		Cell (18650)	Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	2001–2015 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 19±3%			[91, 92]
2017, 2019	Energy storage	Electronics	Cell (tentative)	Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	1993–2005 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 21±3%			[91, 92]
2018	Battery production	"small-scale" "especially cylindrical"	Cell	Cumulative production (GWh)	Price (USD/kWh)	1991–2018 (annual)	"learning factor (price experience factor, PEF) describes the achievable cost reduction resulting from a doubling of the accumulated production volume" Log-log linear fit (tentative)	Price experience factor: ≈15%		"Source: Fraunhofer ISI based on [Pillot 2018, Takeshita 2018]"	[75]

continued on next page...

Table S2 – continued from previous page

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)	Results (as reported)	R^2	Other	Ref.
2018	Battery production	"large-scale" "(pouch and prismatic)"	Cell	Cumulative production (GWh)	Price (USD/kWh)	2010–2018 (annual)	"learning factor (price experience factor, PEF) describes the achievable cost reduction resulting from a doubling of the accumulated production volume" Log-log linear fit (tentative)	Price experience factor: ≈15%		"Source: Fraunhofer ISI based on [Pillot 2018, Takeshita 2018]"	[75]
2019	Energy storage	Electronics	Cell (tentative)	Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	1995–2016 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 30±2%			[92]
2019	Energy storage	Electric vehicles		Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	2010–2017 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 19±5%			[92]
2019	Energy storage	Residential		Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	2013–2017 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 15±4%			[92]
2019	Energy storage	Utility		Cumulative installation (GWh_{cap})	Price (2015USD /kWh_{cap})	2010–2017 (annual)	$P(x) = Ax^{-b}$ and $ER = 1 - 2^{-b}$	Experience rate: 16±5%			[92]
2019	Batteries	Electric vehicles and stationary storage	Pack	Cumulative volume	Price (2018USD /kWh)		"for every doubling of cumulative volume, we observe an 18% reduction in price"	Learning rate: 18%			[9]

continued on next page...

Table S2 – continued from previous page

Date	Research context	Battery application	Level	Independent variable(s) (x, y, z)	Dependent variable (P)	Time period used to fit	Functional form (as reported)	Results (as reported)	R^2	Other	Ref.
2019	Electric vehicles	Electric vehicles	Materials	Cumulative installed capacity (V_{MS})	Active materials cost ($MatC_t$)	2010–2015 (annual)	$MatC_t = (MatC_0 - MinC_0)\left(\frac{V_{MS,t}}{V_{MS,0}}\right)^{b_{MS}} + MinC_t$ and $LR_{MS} = 1 - 2^{b_{MS}}$ where $MinC_t$ is mineral cost at time t, $MatC_t$ is material cost at time t, and $t = 0$ gives initial costs	Learning rate (LR_{MS}): 3.52%	0.99		[93]
2019	Electric vehicles	Electric vehicles	Pack	Cumulative installed capacity (V_{BP})	Battery pack price (MPP_t)	2010–2016 (annual)	$BPP_t = (BPP_0 - MatC_0)\left(\frac{V_{BP,t}}{V_{BP,0}}\right)^{b_{BP}} + MatC_t$ and $LR_{BP} = 1 - 2^{b_{BP}}$ where $MatC_t$ is material cost at time t, BPP_t is battery pack price at time t, and $t = 0$ gives initial costs	Learning rate (LR_{BP}): 16.49±4.52%	0.82		[93]

[a]Blank table entries result from either a lack of information or clarity in the original source. A "tentative" label is applied to data that are strongly implied by the source, but not explicitly stated.

[b]The functional forms reported here are those reported, if available, by the authors of the studies summarized in this table. When possible, variables have been represented by consistent symbols (x and y for independent variables, P for the dependent variable). Progress ratio (PR) and learning rate (LR) were abbreviated. The functional forms summarized here are not necessarily consistent with each other or the models employed in this work.

[c]While not explicitly stated in the cited report, compound annual growth rates are presumed to be defined by the formula: $r = \left(\frac{P_{x_2}}{P_{x_1}}\right)^{\frac{1}{x_2 - x_1}} - 1$.

4 Supplementary figures

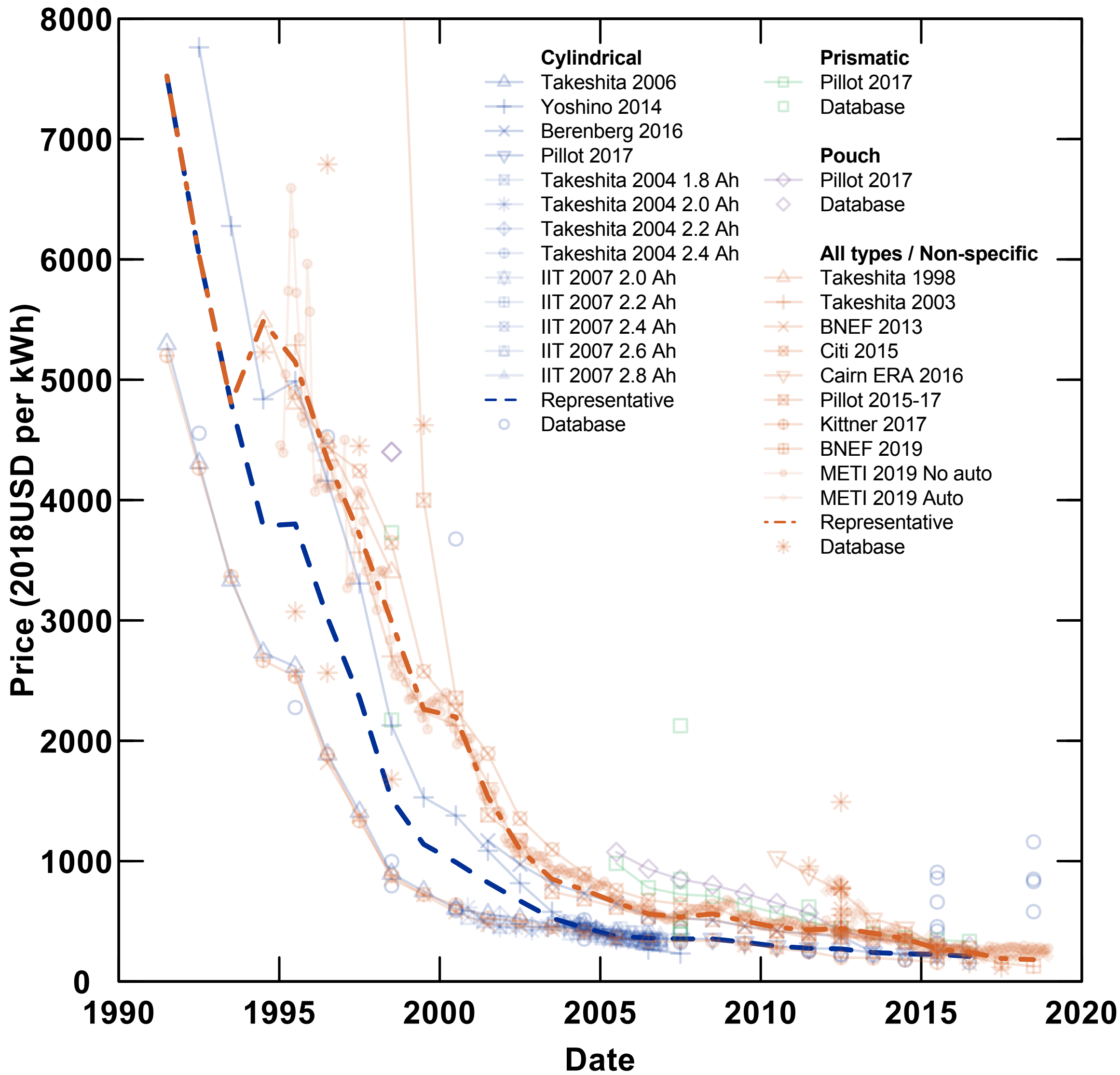


Figure S2: Lithium-ion cell price data series on a non-logarithmic dependent axis. Time series and single-year records of lithium-ion cell prices for cylindrical (blue), prismatic (green), pouch (purple), and all types (orange) of cells, as well as representative price series for cylindrical (blue, bold, dashed) and all types (orange, bold, dashed) of cells. Records that did not specify cell type are included with series representing all types of cells.

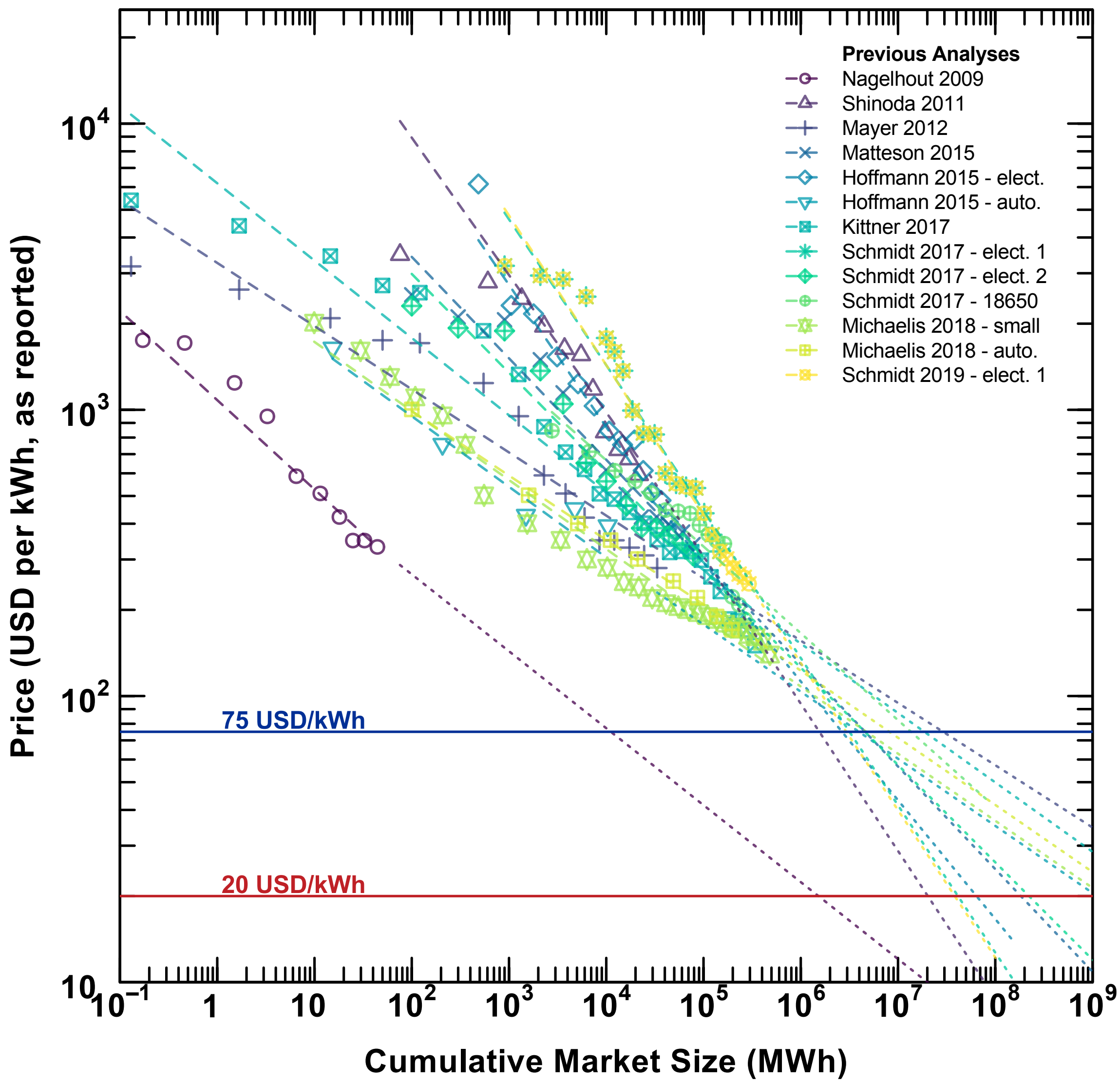


Figure S3: Previous analyses of lithium-ion cell price versus cumulative market size and projections assuming exponential growth in annual market size. Previously reported single-factor analyses of lithium-ion cells' price per energy capacity vs. cumulative market size (*e.g.* production, installation, sales, etc.) as measured in energy capacity. Trend lines plotted were extracted from previous analyses' plots. The requisite cumulative market size projections assume exponential growth in annual market size, as extrapolated from the market size data used in each analysis.

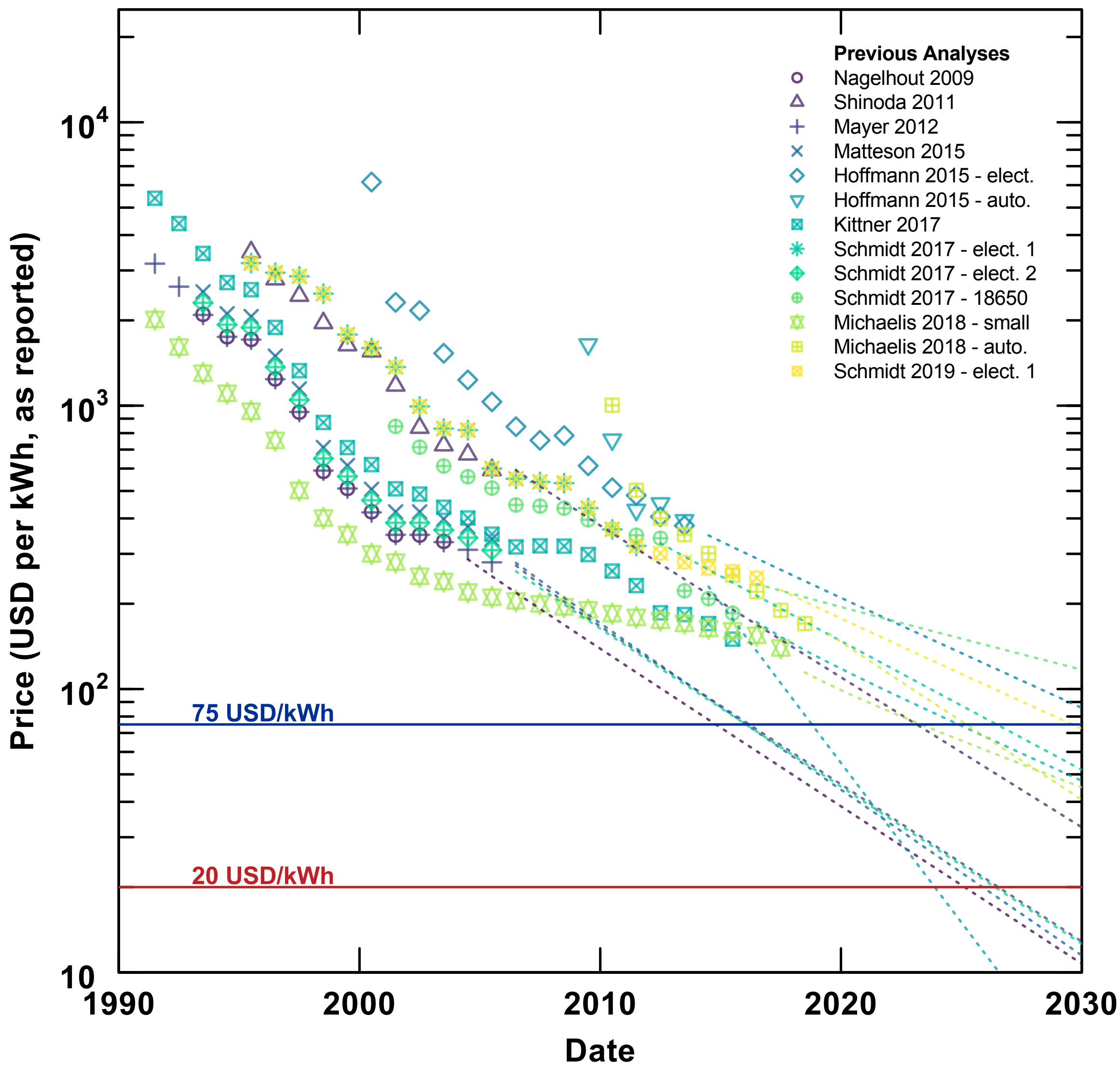


Figure S4: Previous analyses of lithium-ion cell price versus time and projections assuming exponential growth in annual market size. Previously reported single-factor analyses of lithium-ion cells' price per energy capacity vs. cumulative market size (*e.g.* production, installation, sales, etc.) as measured in energy capacity. The requisite cumulative market size projections assume exponential growth in annual market size, as extrapolated from the market size data used in each analysis.

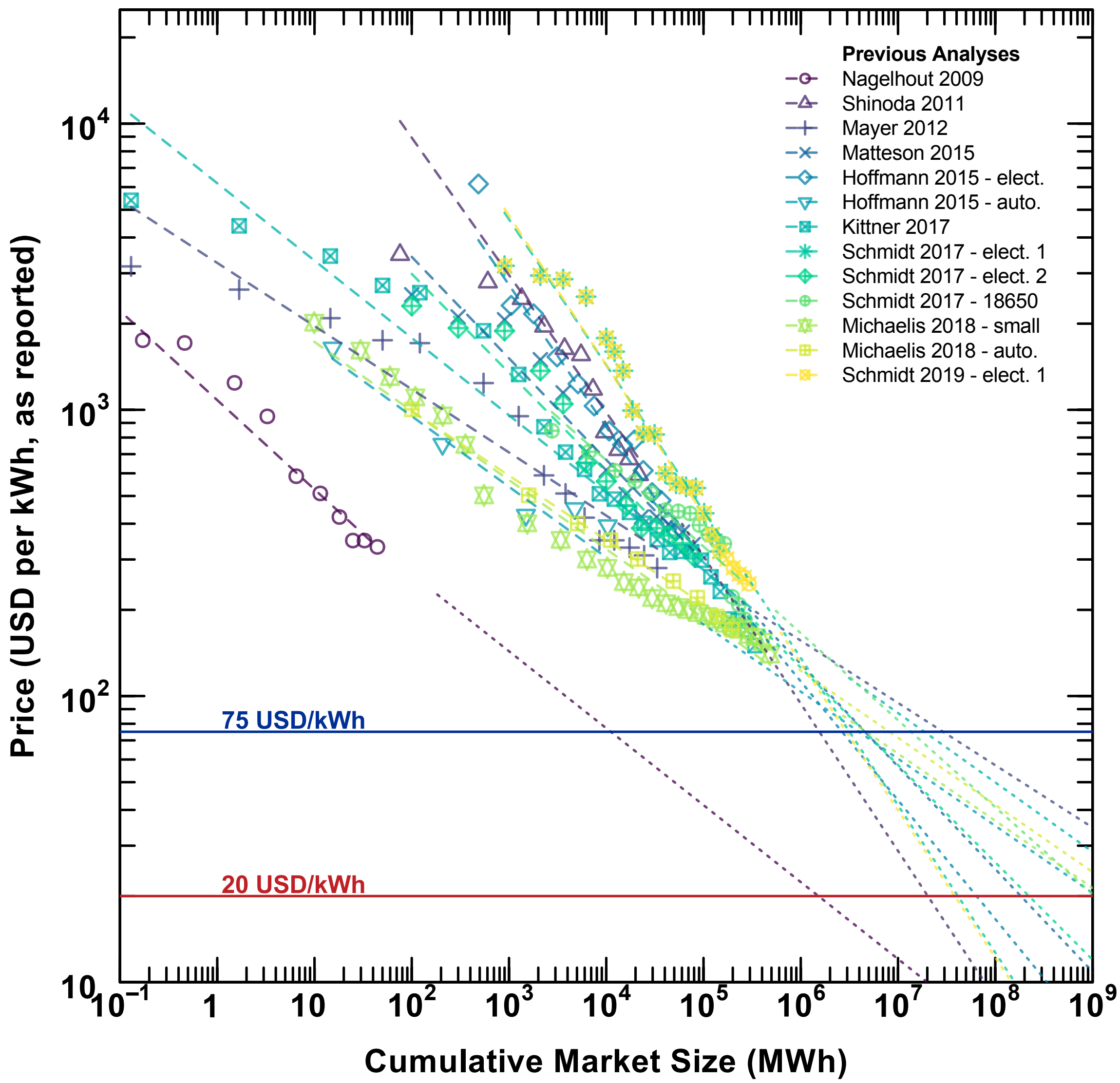


Figure S5: Previous analyses of lithium-ion cell price versus cumulative market size and projections assuming exponential growth in cumulative market size. Previously reported single-factor analyses of lithium-ion cells' price per energy capacity vs. cumulative market size (*e.g.* production, installation, sales, etc.) as measured in energy capacity. Trend lines plotted were extracted from previous analyses' plots. The requisite cumulative market size projections assume exponential growth in cumulative market size, as extrapolated from the market size data used in each analysis

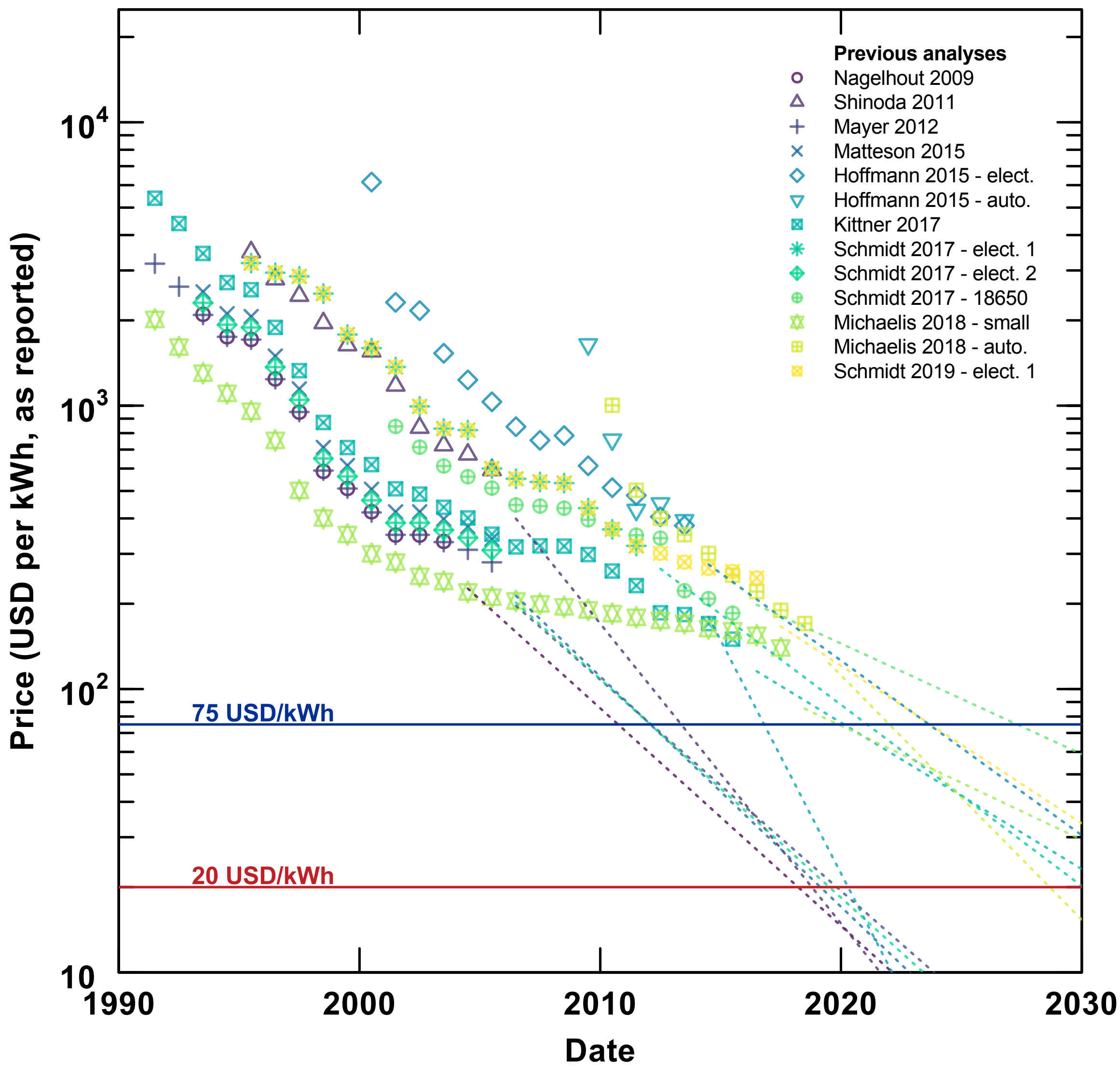


Figure S6: Previous analyses of lithium-ion cell price versus time and projections assuming exponential growth in cumulative market size. Previously reported single-factor analyses of lithium-ion cells' price per energy capacity vs. cumulative market size (*e.g.* production, installation, sales, etc.) as measured in energy capacity. The requisite cumulative market size projections assume exponential growth in cumulative market size, as extrapolated from the market size data used in each analysis.

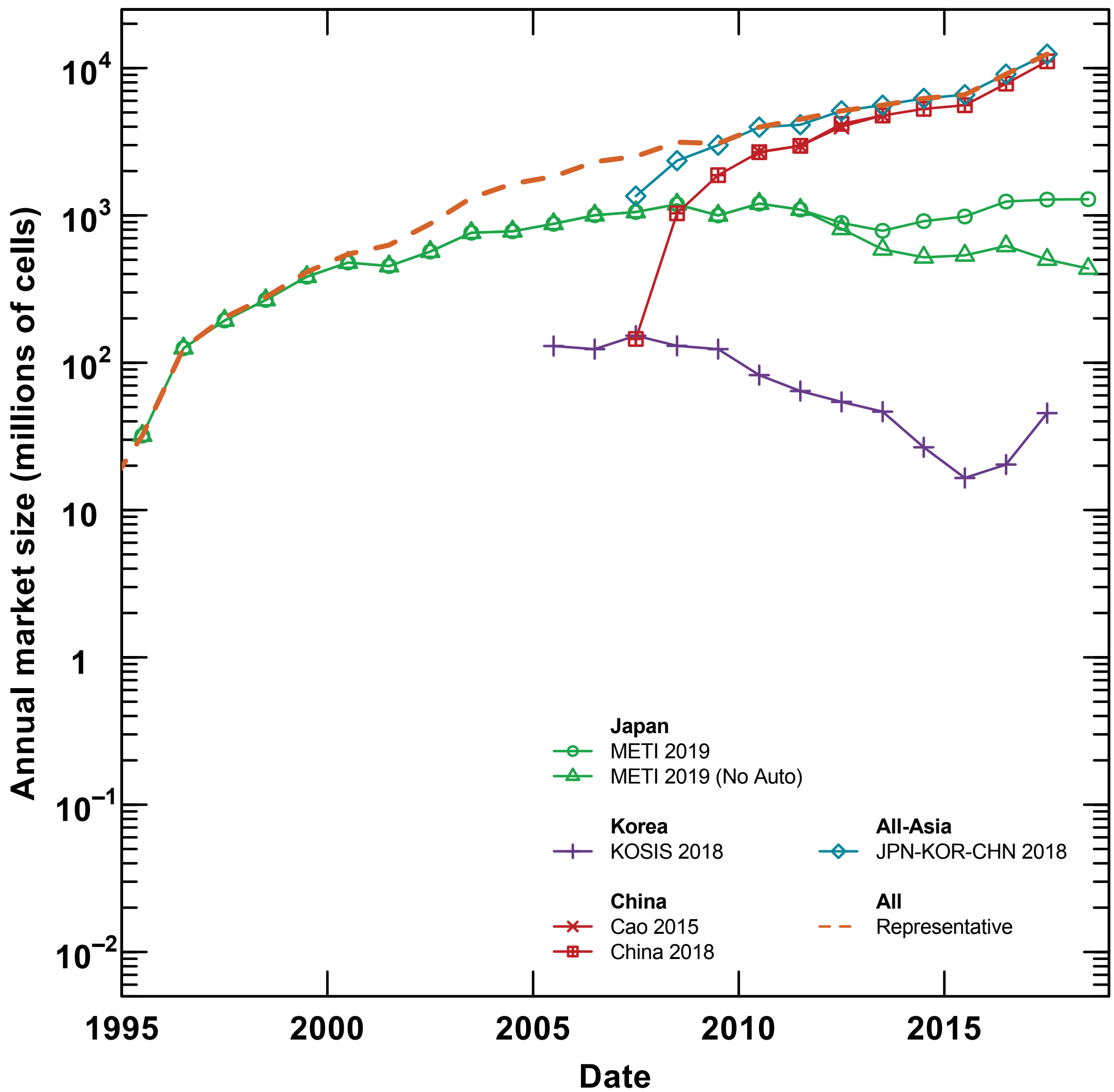


Figure S7: Lithium-ion cell market size series for Japan, Korea, and China, their sum, and the representative series for the market size of all types of cells.

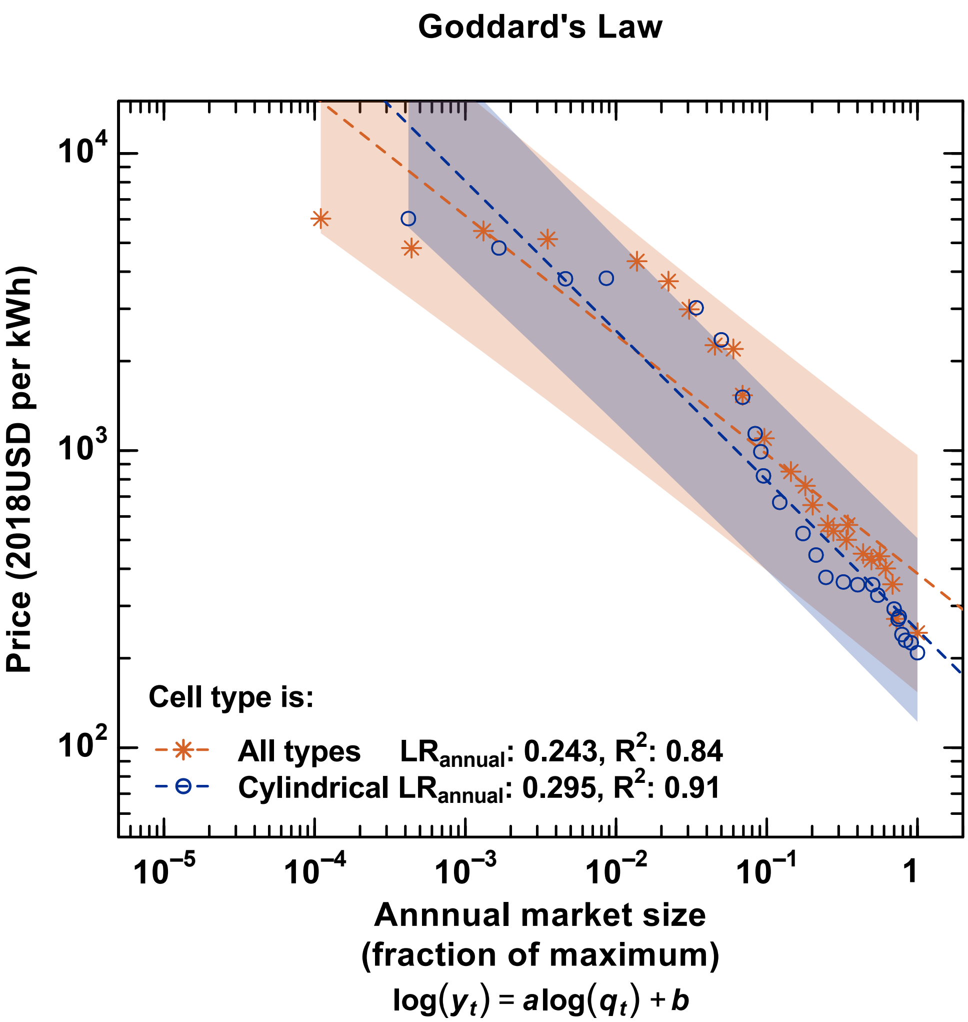


Figure S8: Lithium-ion cell price regressed against annual market size (equation 3) as measured in number of cells, for the years 1992 through 2016, for all shapes of cells (orange asterisk marks) and cylindrical cells (blue circles).

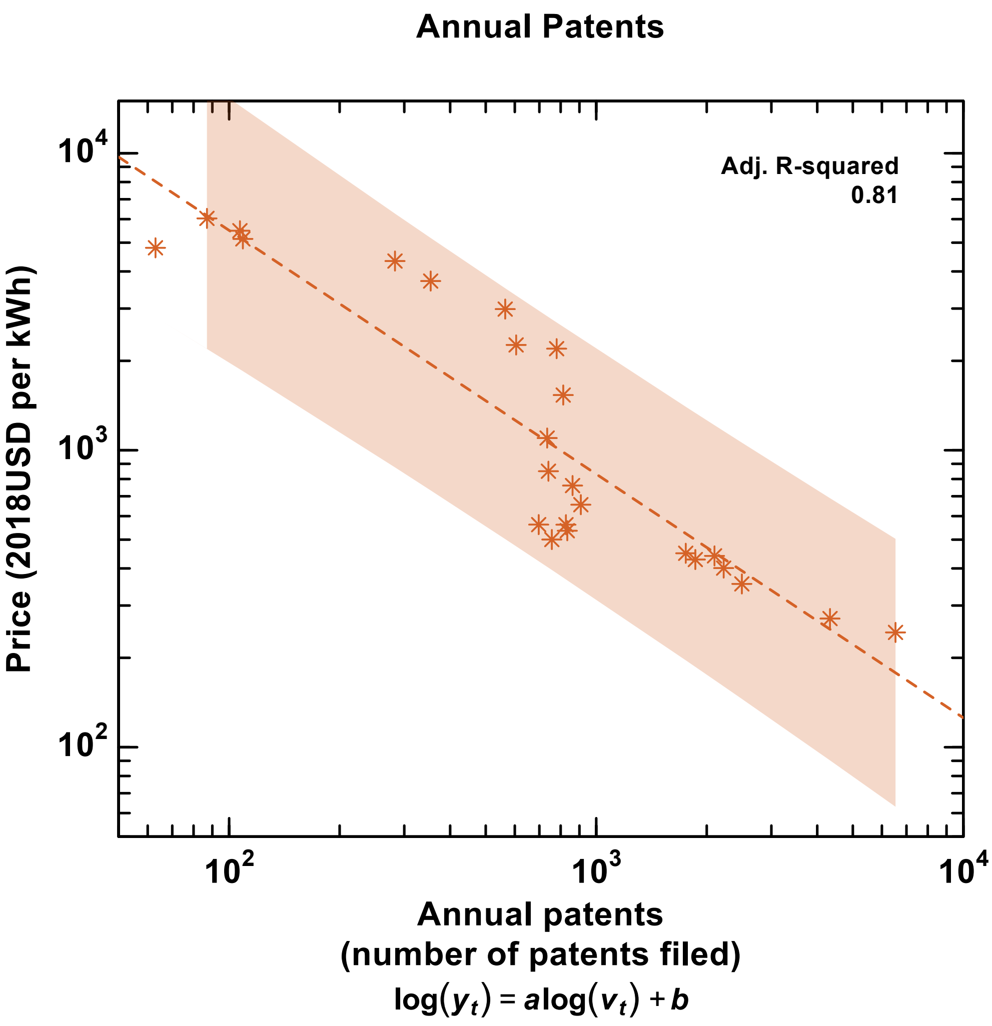


Figure S9: Lithium-ion cell price regressed against annual patent filings (equation 5), for the years 1992 through 2016.

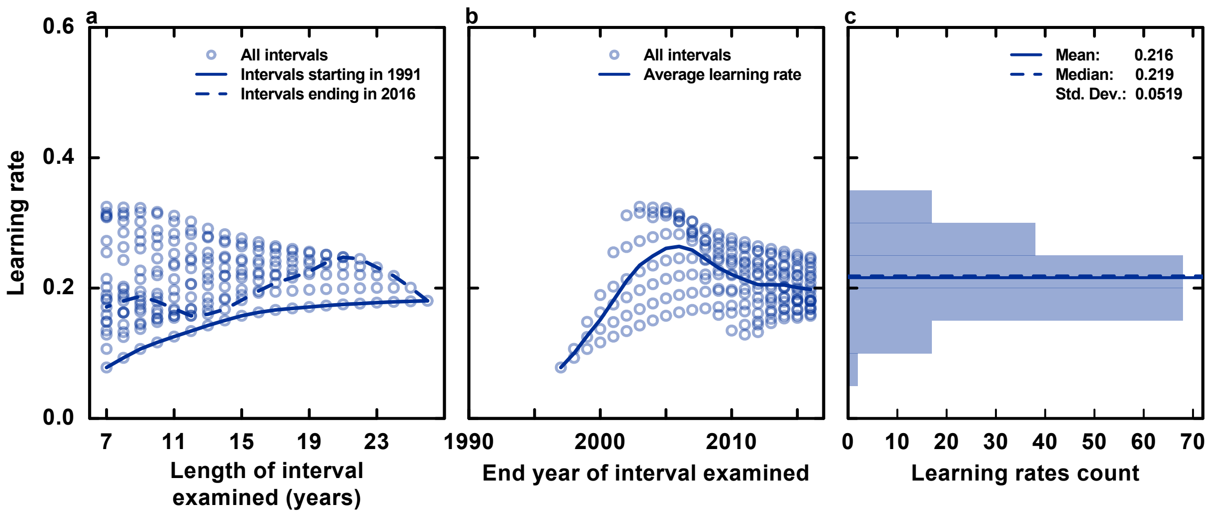


Figure S10: Learning rates calculated for every interval of seven or more years between 1991 and 2016 using representative cylindrical cell price per energy capacity and cumulative energy capacity market size series for all types of cells, plotted by interval length (a) or interval end year (b), along with a histogram of all learning rates calculated (c).

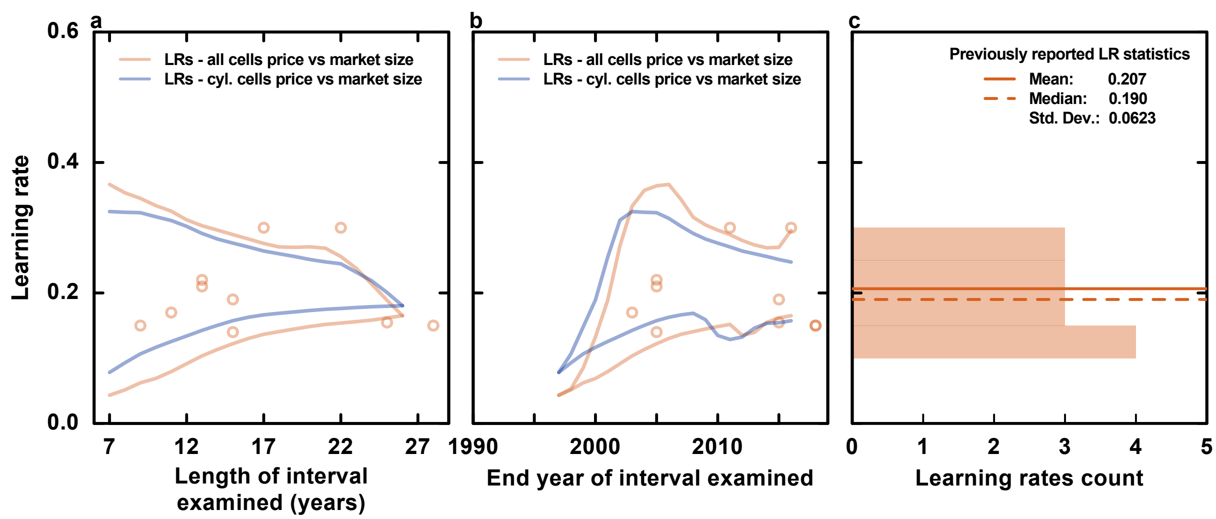


Figure S11: Previously reported learning rates (orange circles) along with the minimum and maximum values obtained when fitting equation 2 to price series for either all types of cells (orange) or cylindrical cells (blue) and the cumulative energy capacity market size series for the years 1991–2016. These results are plotted by interval length (a) or interval end year (b), along with a histogram of all previously reported learning rate estimates (c).

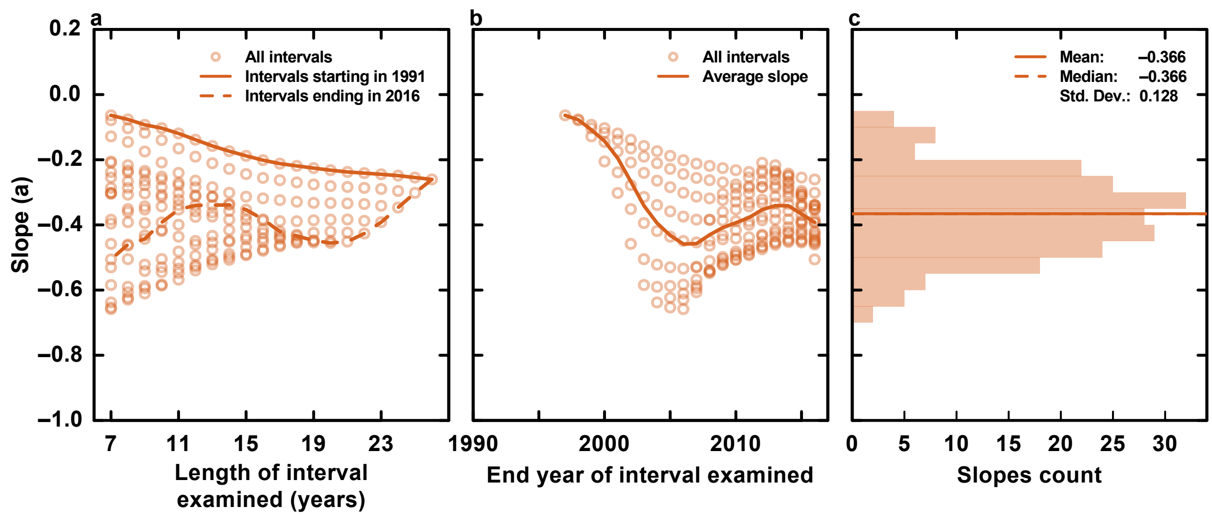


Figure S12: Slopes of the linear model fit to logarithmized price per energy capacity for all types of cells and logarithmized cumulative energy capacity market size for all types of cells, calculated for every interval of seven or more years between 1991 and 2016, plotted by interval length (a) or interval end year (b), along with a histogram of all slopes calculated (c).

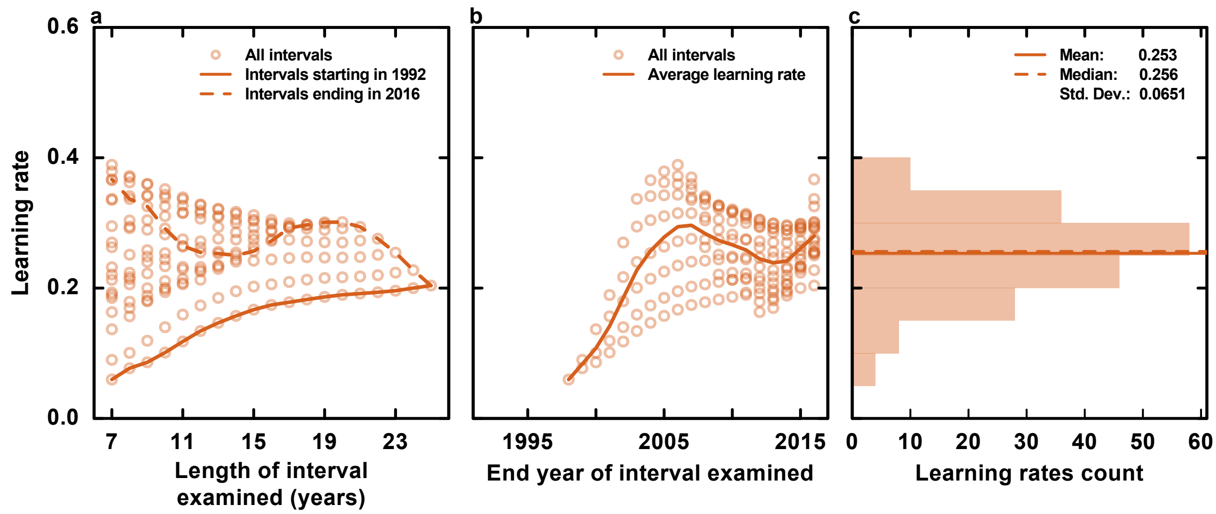


Figure S13: Learning rates calculated for every interval of seven or more years between 1992 and 2016 using representative price per energy capacity for all types of cells and cumulative market size for all types of cells as measured in number of cells, plotted by interval length (a) or interval end year (b), along with a histogram of all learning rates calculated (c).

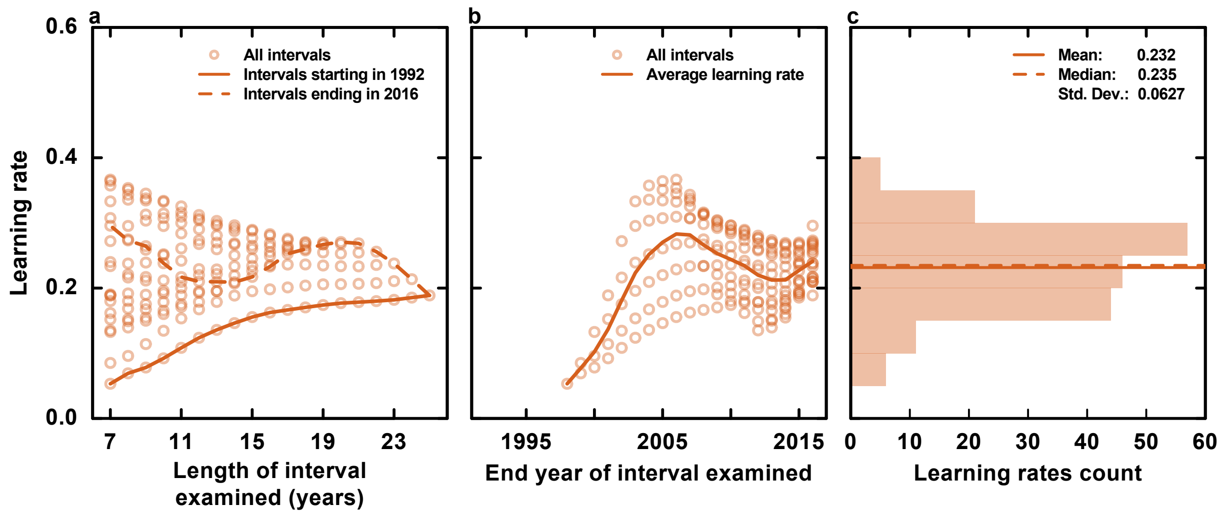


Figure S14: Learning rates calculated for every interval of seven or more years between 1992 and 2016 using representative price per energy capacity for all types of cells and cumulative market size for all types of cells as measured in energy capacity, plotted by interval length (a) or interval end year (b), along with a histogram of all learning rates calculated (c).

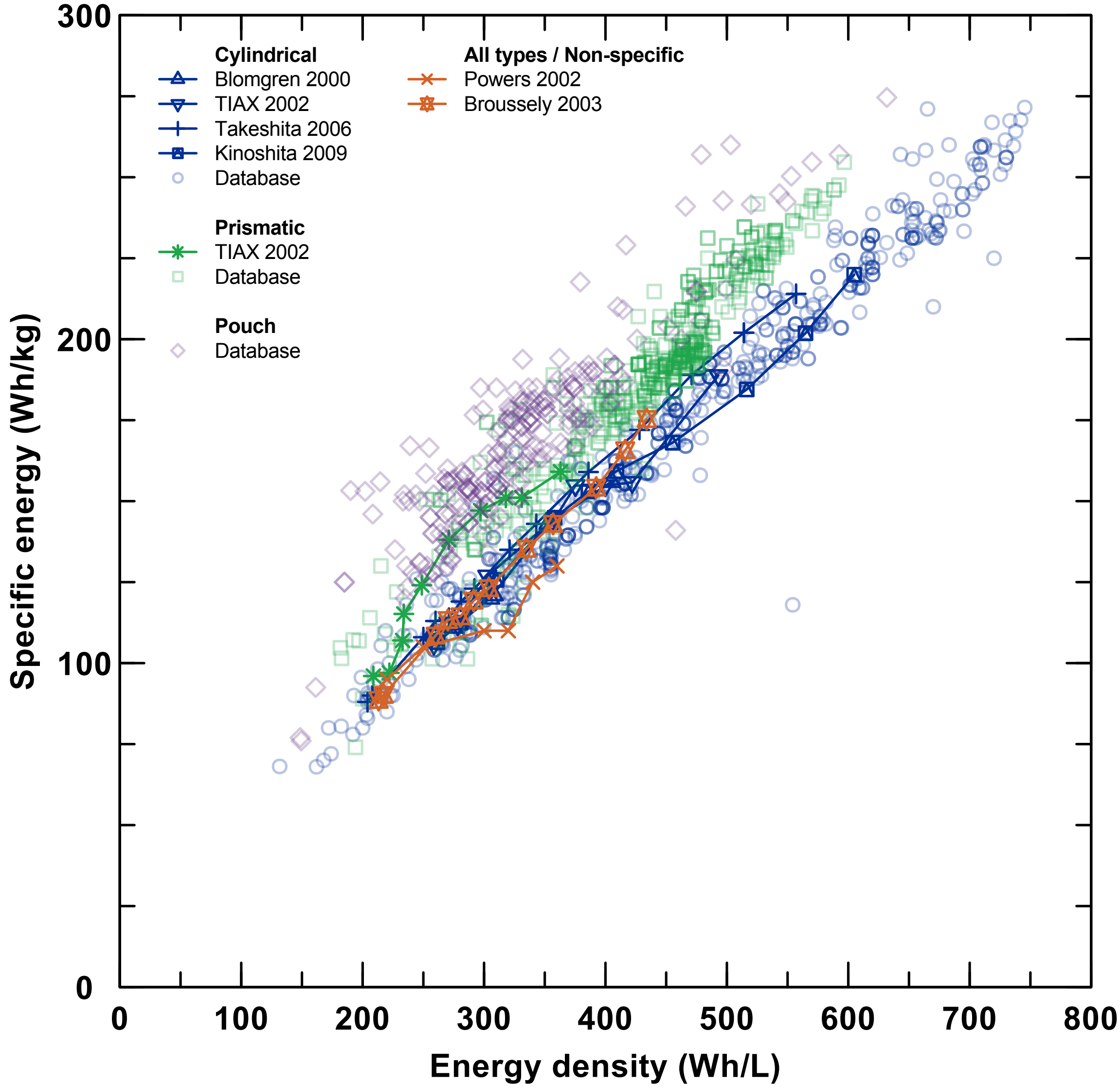


Figure S15: Nameplate specific energy and energy density values for cylindrical (blue circles), prismatic (green squares), and pouch cells (purple diamonds) for commercial cells between 1991 and 2018, as recorded in the database, as well as previously reported trends relating specific energy and energy density.

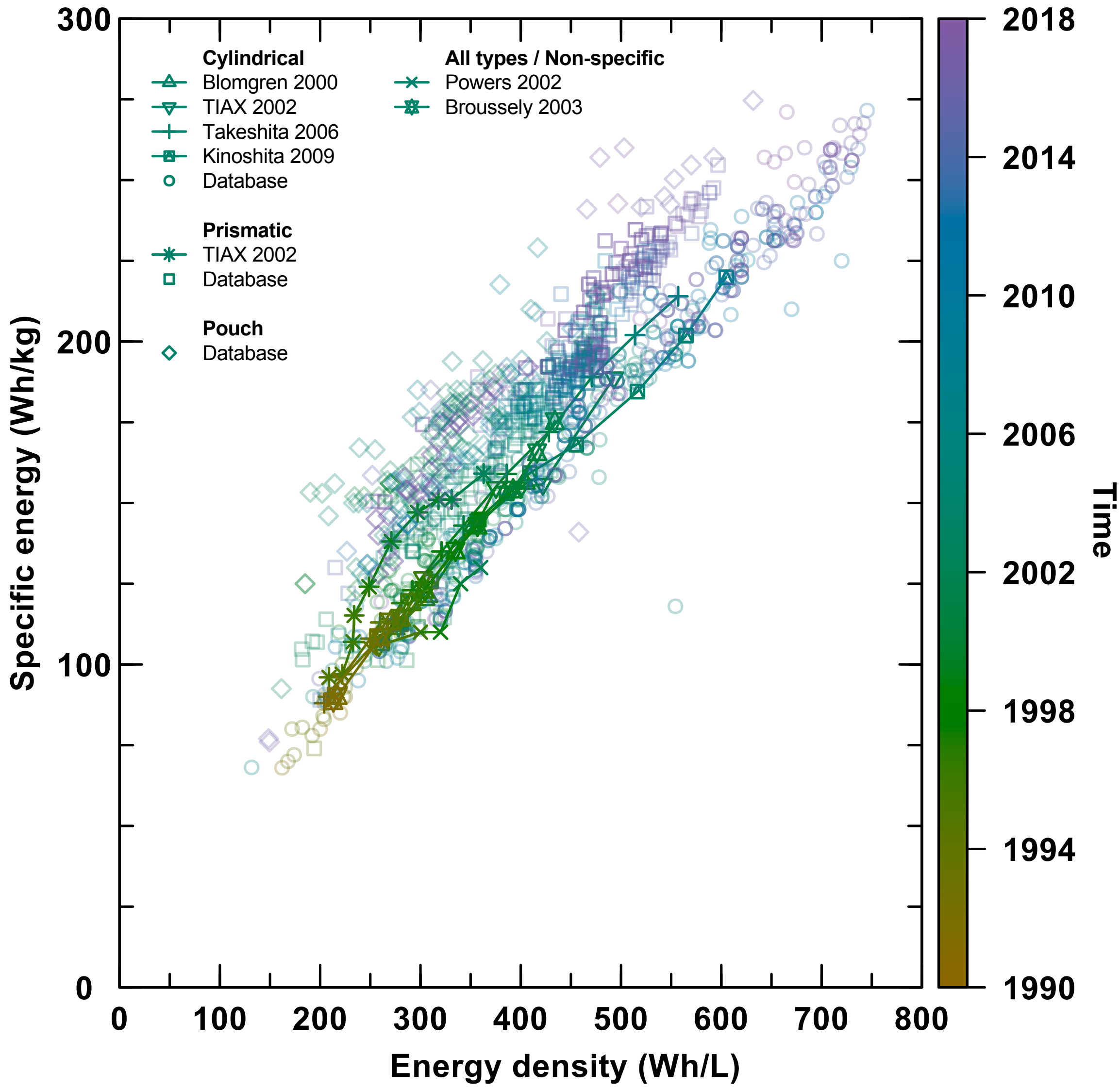


Figure S16: Nameplate specific energy and energy density values for cylindrical (circles), prismatic (squares), and pouch cells (diamonds) for commercial cells between 1991 and 2018 with year represented by color, as well as previously reported time-resolved series relating specific energy and energy density.

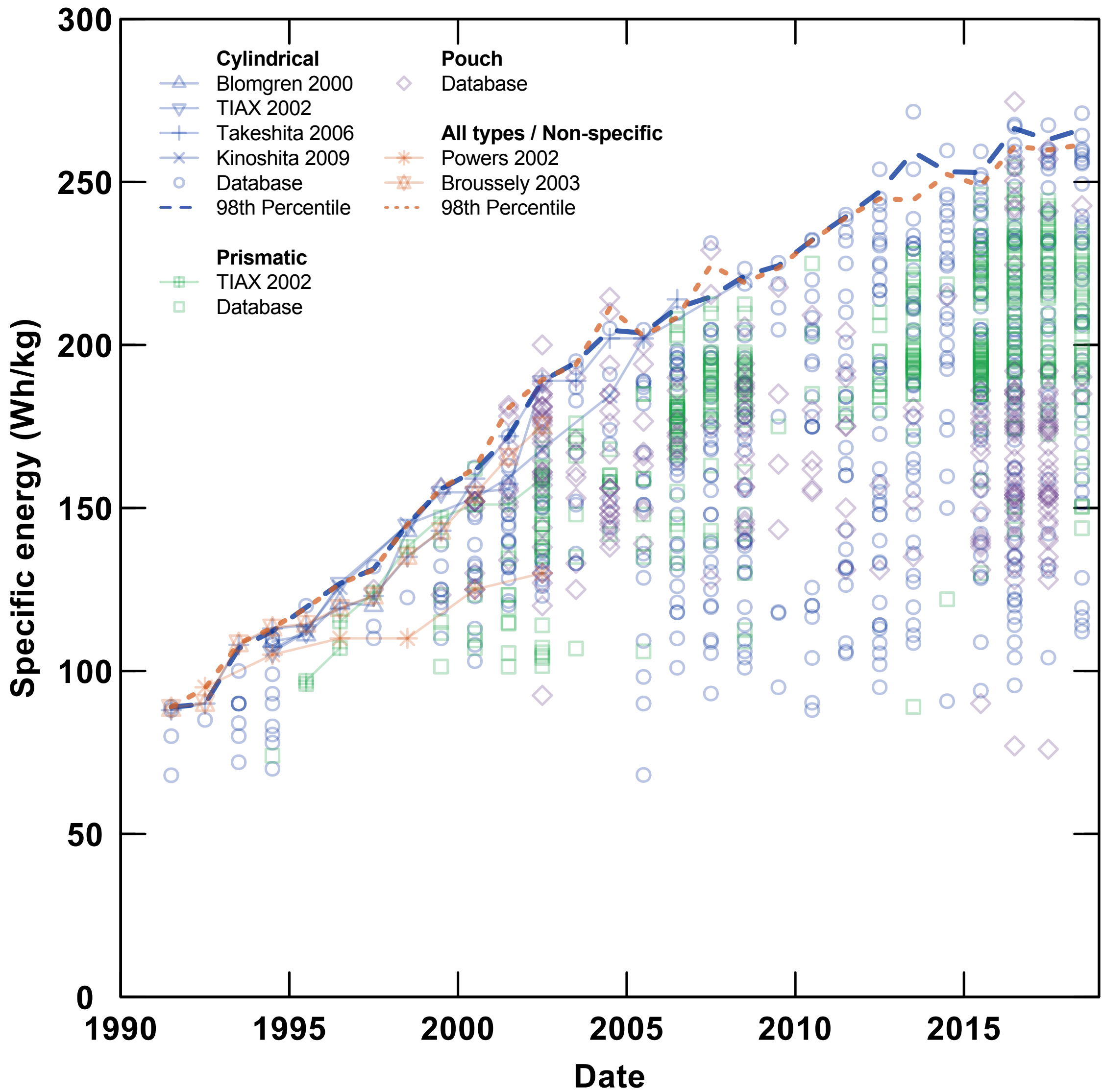


Figure S17: Lithium-ion cell specific energy over time. Time series and single-year records of nameplate specific energy values for lithium-ion cells for cylindrical (blue circles), prismatic (green squares), pouch (purple diamonds), and all types (orange) of cells, as well as representative specific energy series for cylindrical (blue, bold, dashed) and all types (orange, bold, dashed) of cells. Series that did not specify cell type are included with series representing all types of cells.

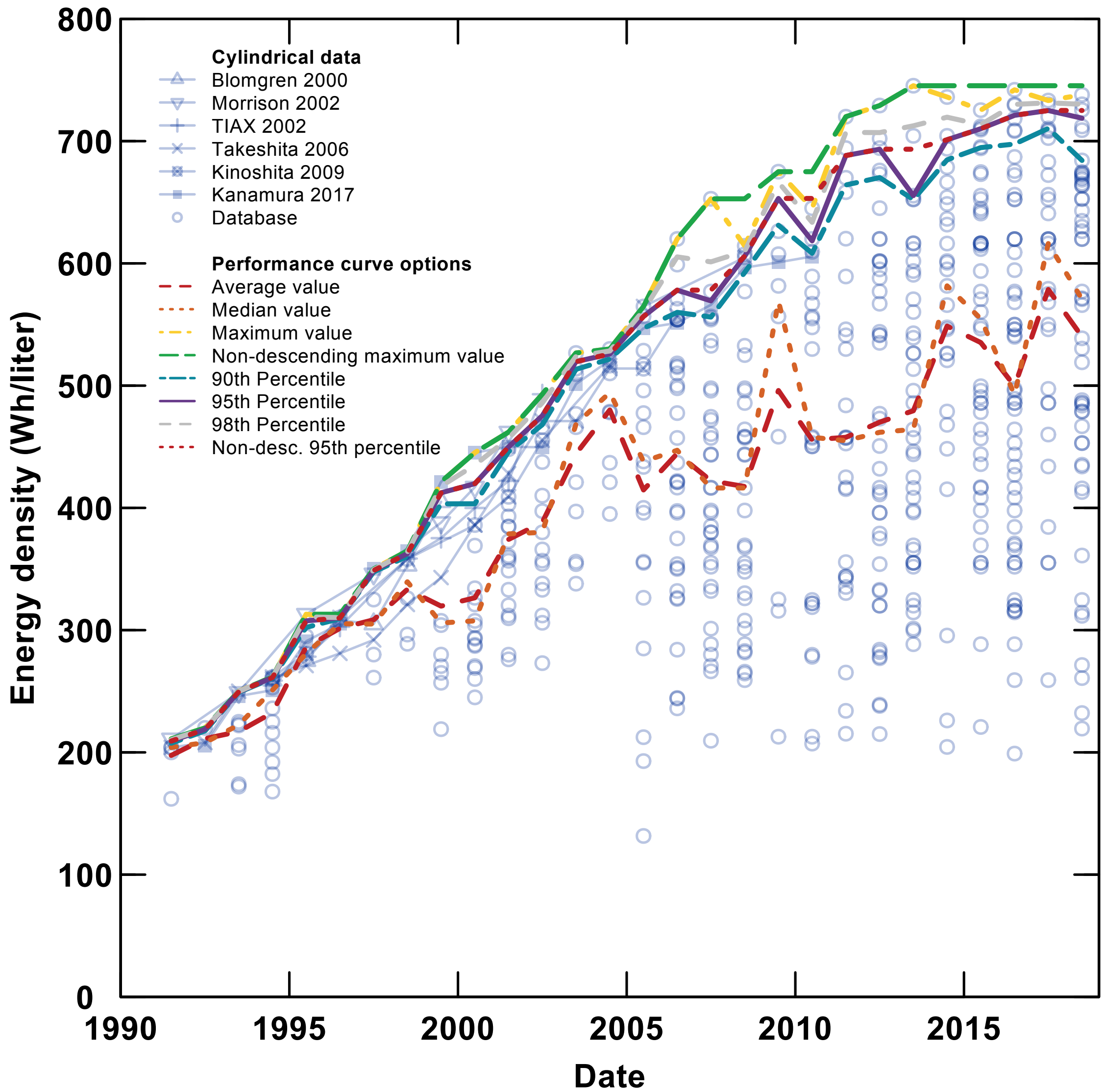


Figure S18: Approaches considered for developing representative series for energy density for cylindrical cells. Time series (various shapes, blue) and single-year records (blue circles) of nameplate energy density values for cylindrical lithium-ion cells, as well as representative series developed using a variety of approaches (various colors, line types).

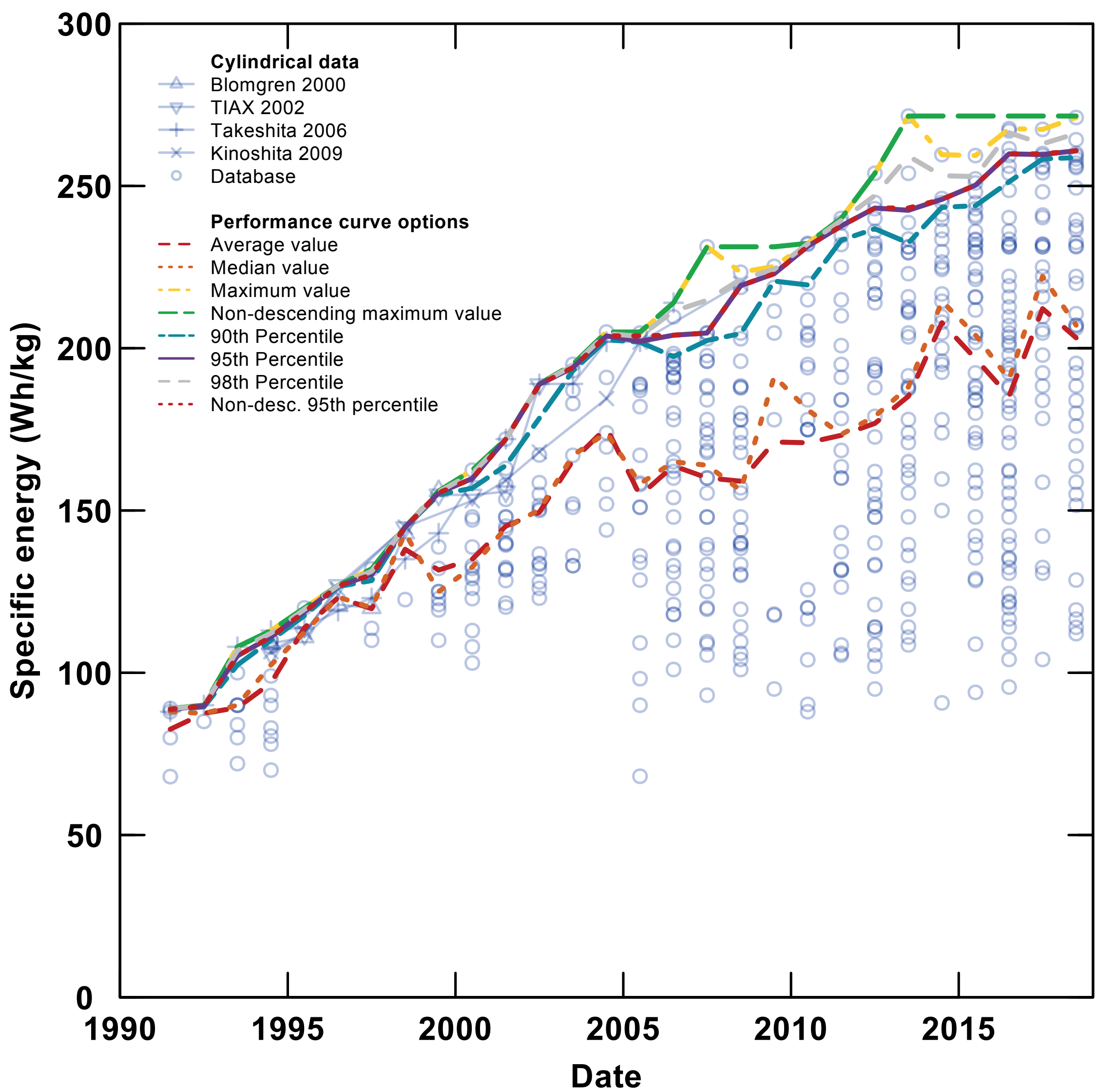


Figure S19: Approaches considered for developing representative series for specific energy for cylindrical cells. Time series (various shapes, blue) and single-year records (blue circles) of nameplate specific energy values for cylindrical lithium-ion cells, as well as representative series developed using a variety of approaches (various colors, line types).

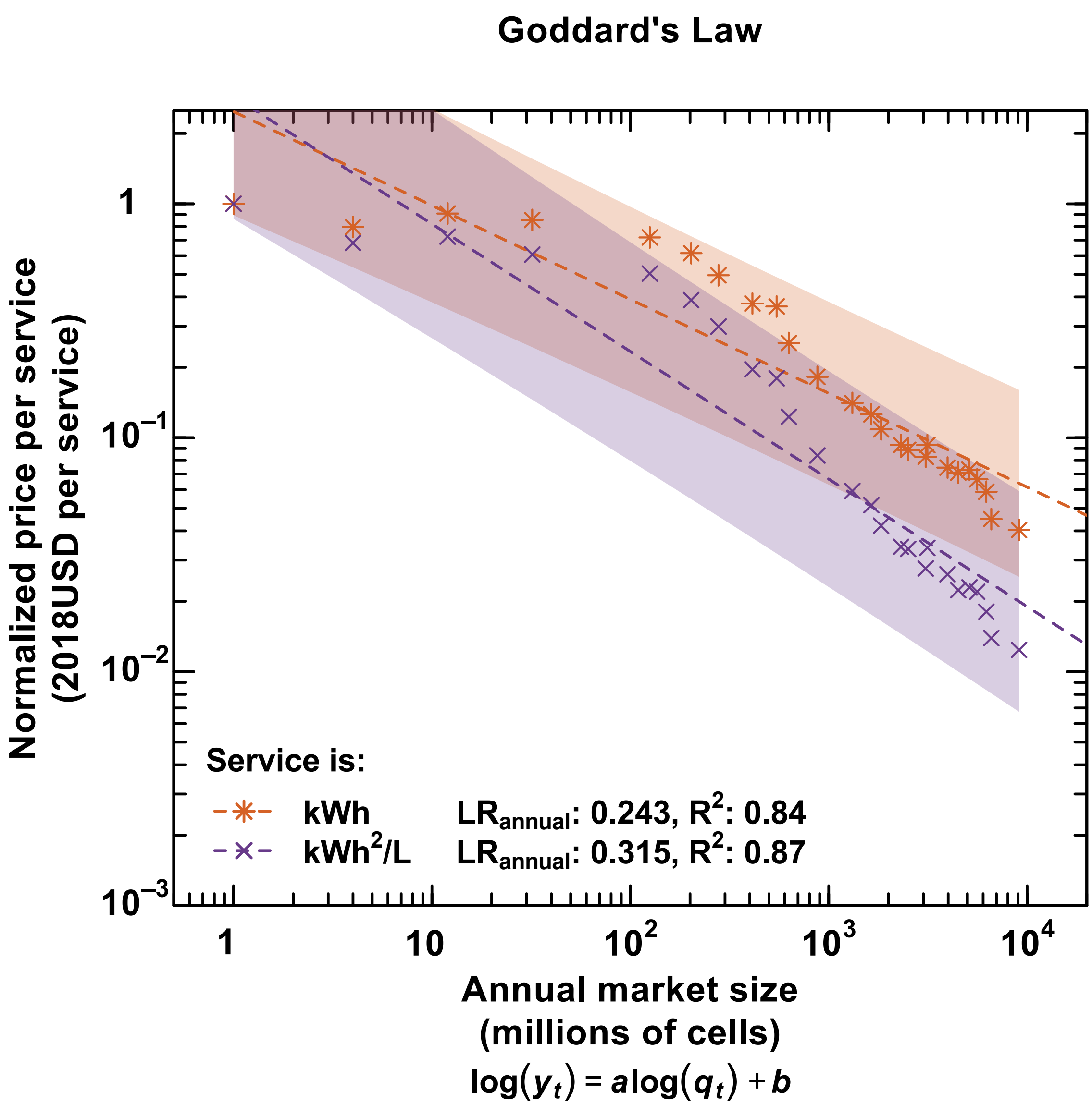


Figure S20: Lithium-ion cell price per energy capacity (orange asterisk marks) and price per service (purple x marks) regressed against annual market size (equation 3) as measured in number of cells, for the years 1992 through 2016. Service includes both energy capacity and energy denisty.

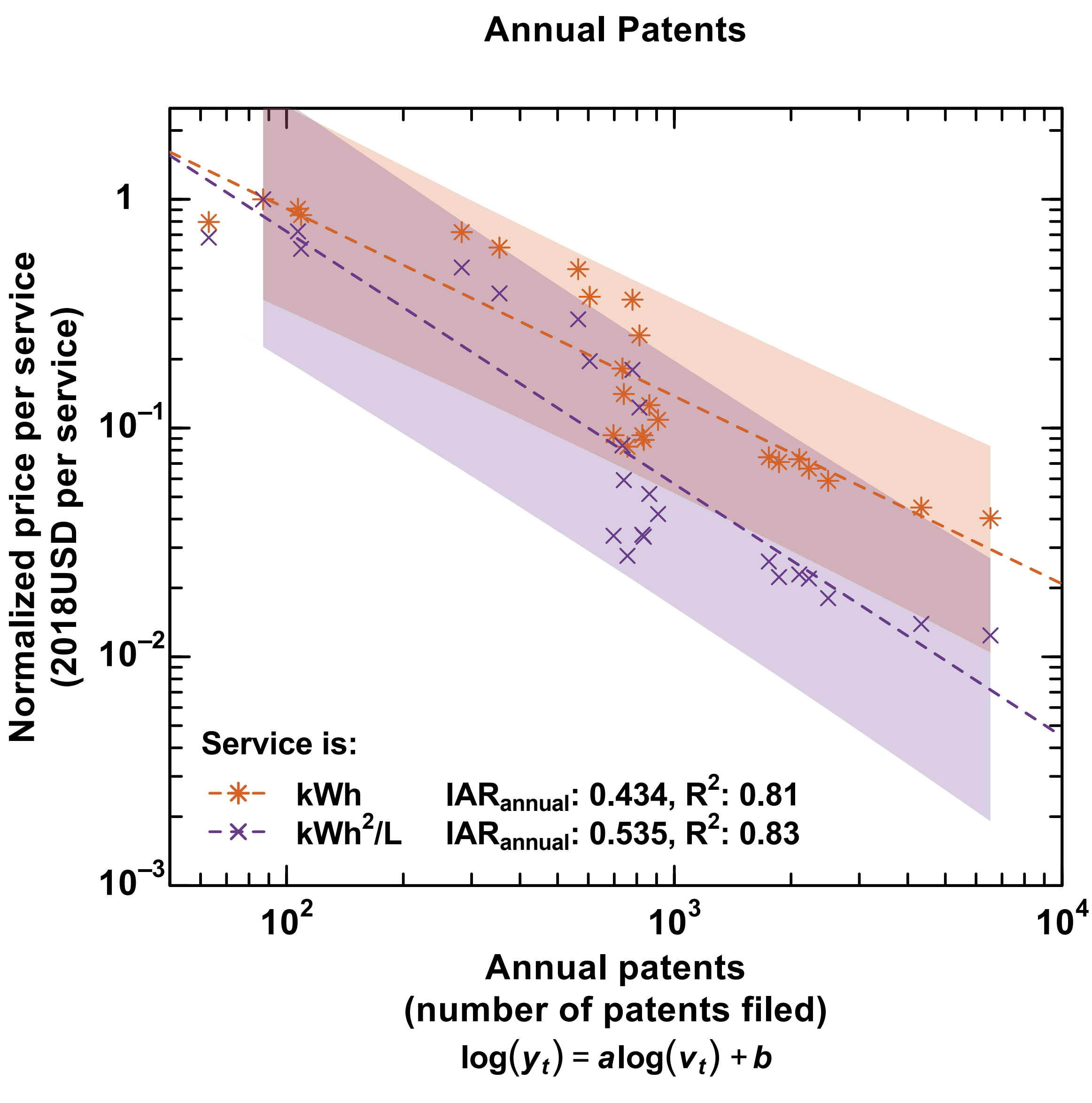
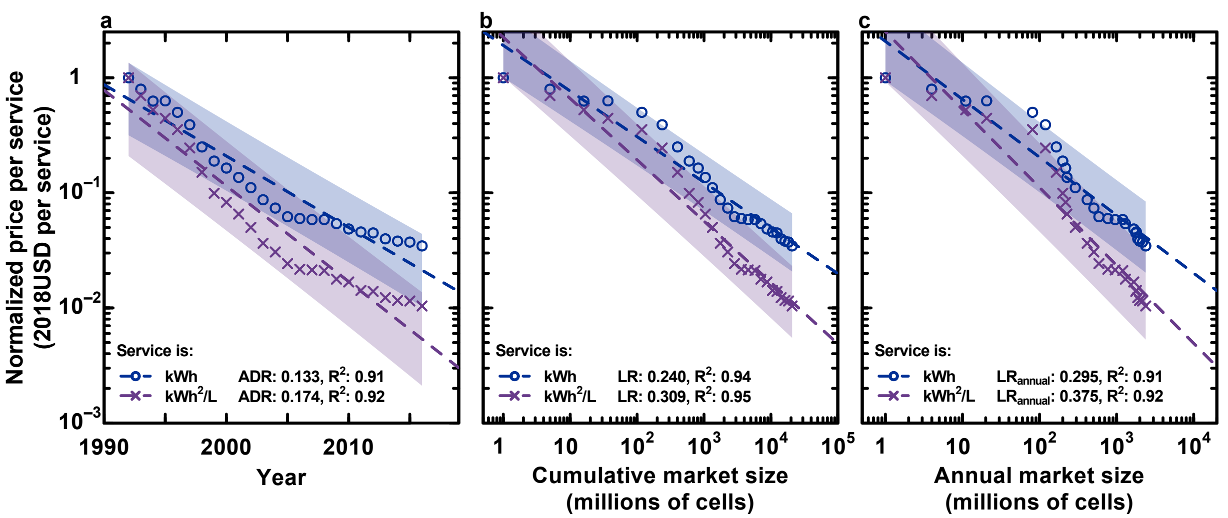


Figure S21: Lithium-ion cell price per energy capacity (orange asterisk marks) and price per service (purple x marks) regressed against annual patent filings (equation 5), for the years 1992 through 2016. Service includes both energy capacity and energy denisty.



$\log(y_t) = at + b$ $\quad$ $\log(y_t) = a\log(x_t) + b$ $\quad$ $\log(y_t) = a\log(q_t) + b$

Figure S22: Lithium-ion cell price per energy capacity (blue circles) and price per service (purple x marks) regressed against year (a), cumulative market size (b), and annual market size (c) for cylindrical cells. Service includes both energy capacity and energy density. Prediction intervals (95% level) are plotted as similarly colored shaded regions. Analyses are restricted to the years 1992 through 2016, and market size is measured in number of cells.

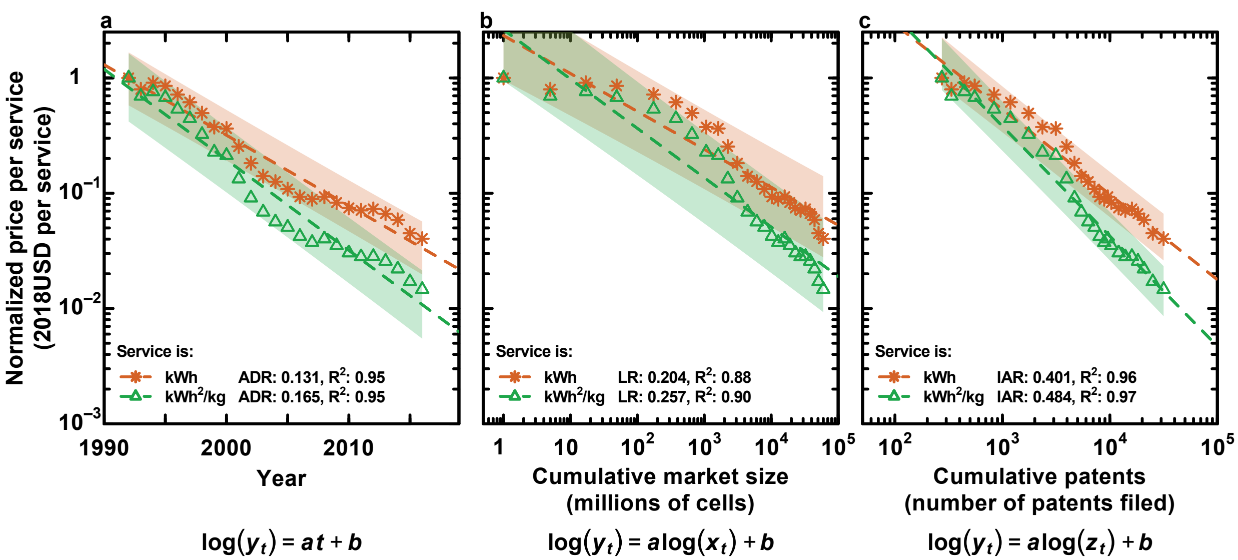


Figure S23: Lithium-ion cell price per energy capacity (orange asterisk marks) and price per service (green triangles) regressed against year (a), cumulative market size (b), and cumulative patent filings (c) for all cell shapes. Service includes both energy capacity and specific energy. Prediction intervals (95% level) are plotted as similarly colored shaded regions. Analyses are restricted to the years 1992 through 2016, and market size is measured in number of cells.

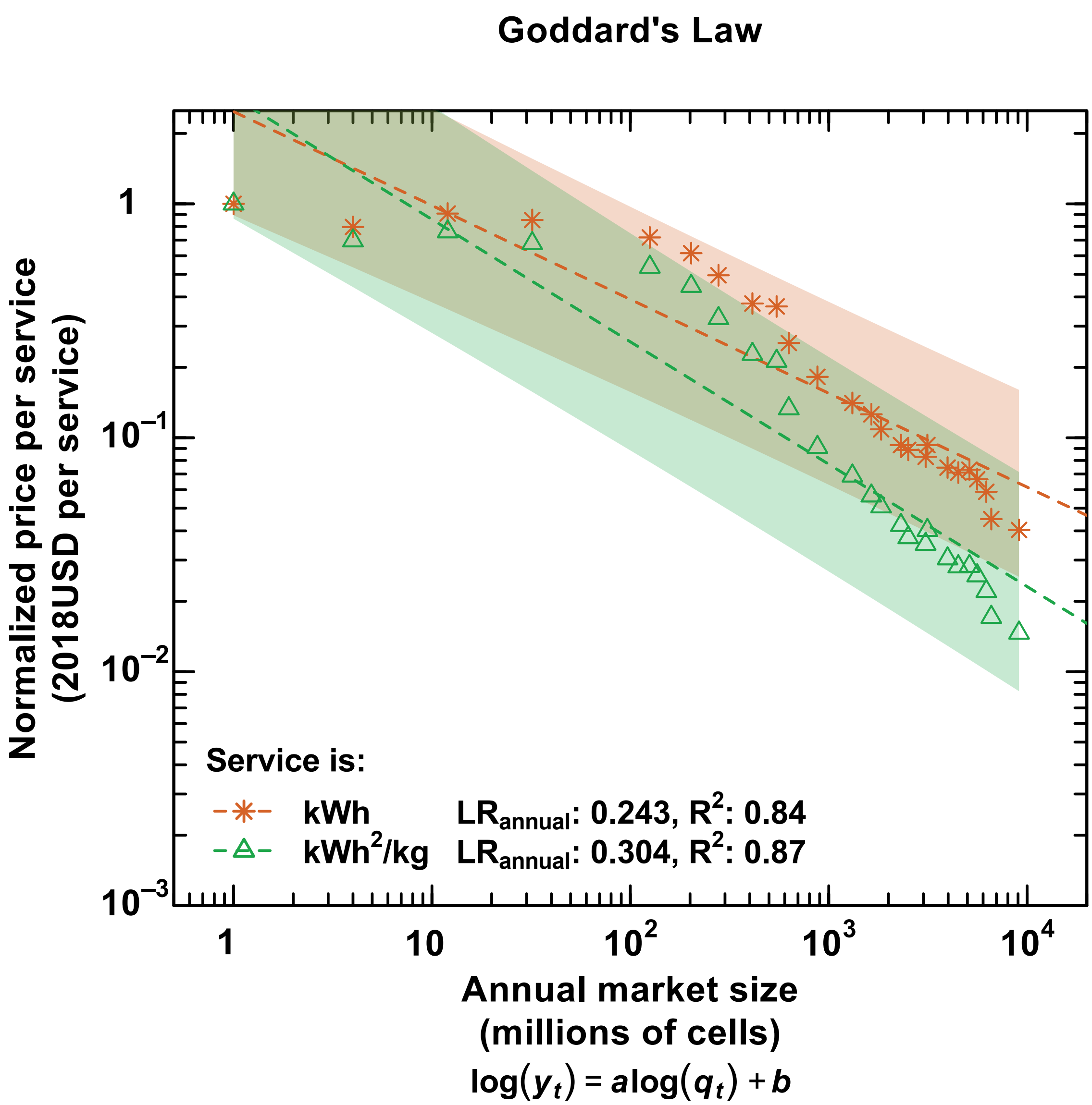


Figure S24: Lithium-ion cell price per energy capacity (orange asterisk marks) and price per service (green triangles) regressed against annual market size (equation 3) as measured in number of cells, for the years 1992 through 2016. Service includes both energy capacity and specific energy.

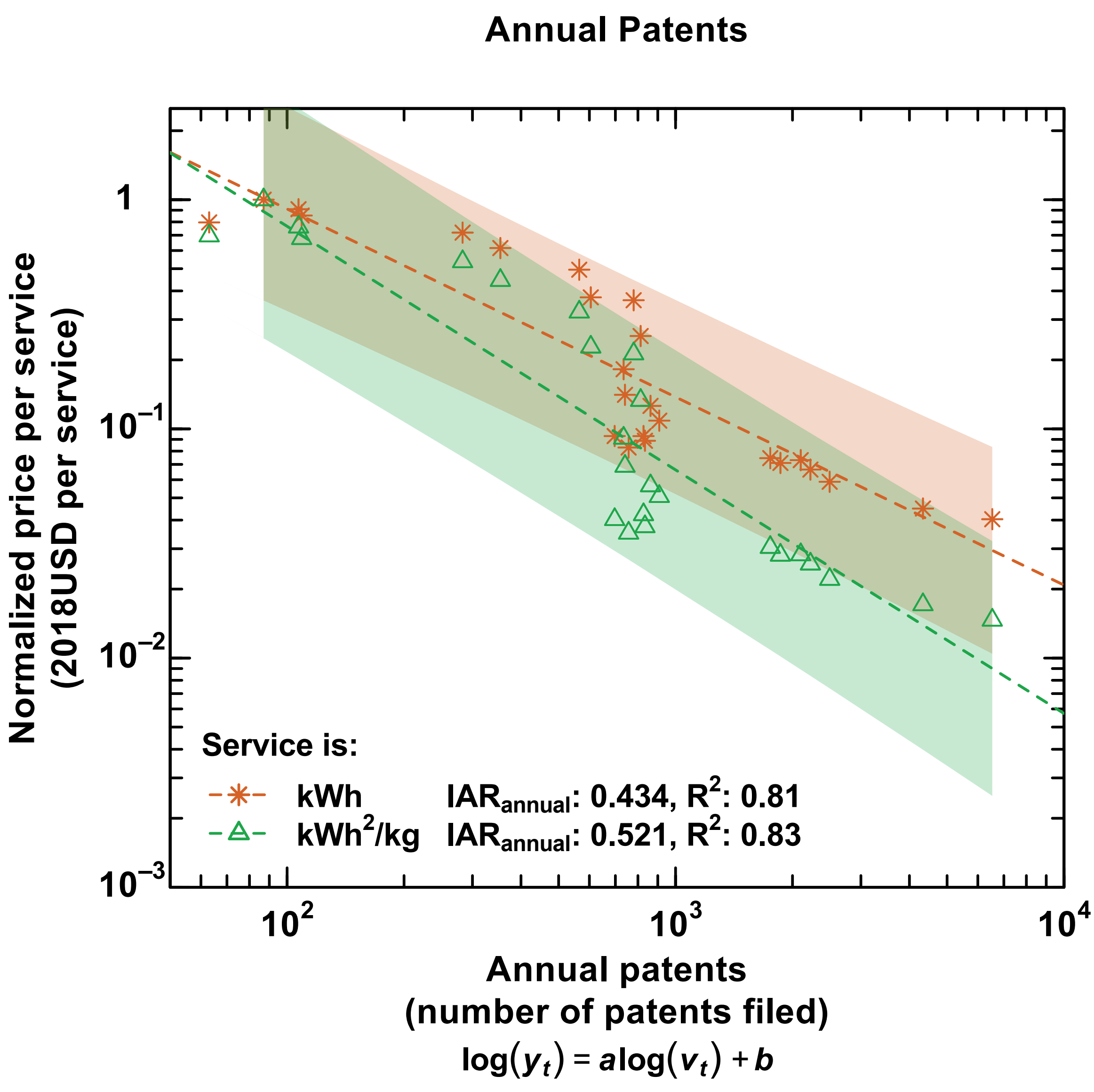


Figure S25: Lithium-ion cell price per energy capacity (orange asterisk marks) and price per service (purple x marks) regressed against annual patent filings (equation 5), for the years 1992 through 2016. Service includes both energy capacity and specific energy.

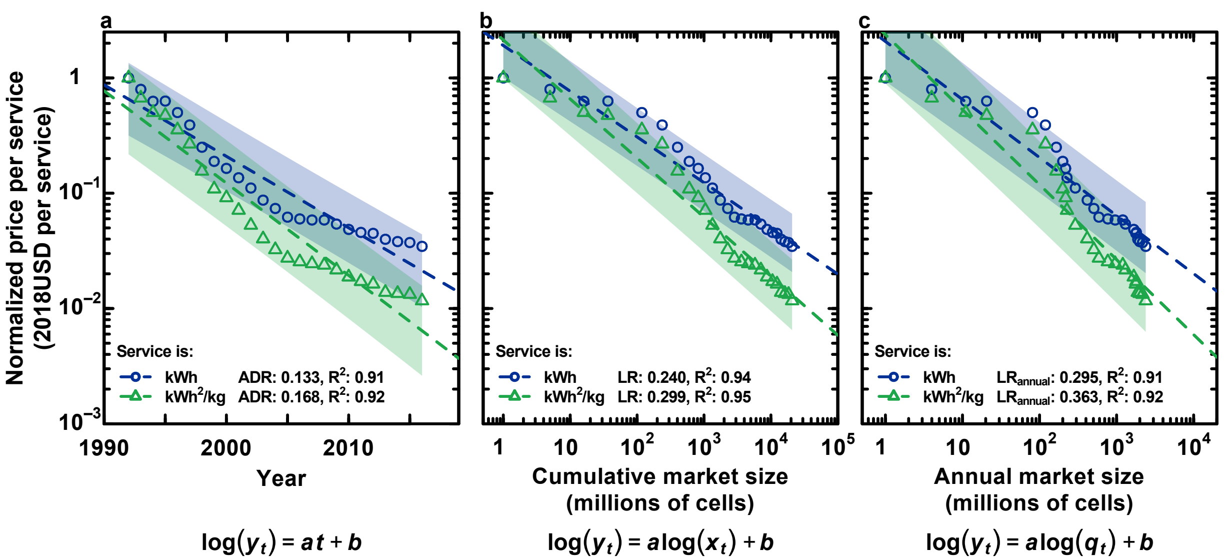


Figure S26: Lithium-ion cell price per energy capacity (blue circles) and price per service (purple x marks) regressed against year (a), cumulative market size (b), and annual market size (c) for cylindrical cells. Service includes both energy capacity and specific energy. Prediction intervals (95% level) are plotted as similarly colored shaded regions. Analyses are restricted to the years 1992 through 2016, and market size is measured in number of cells.

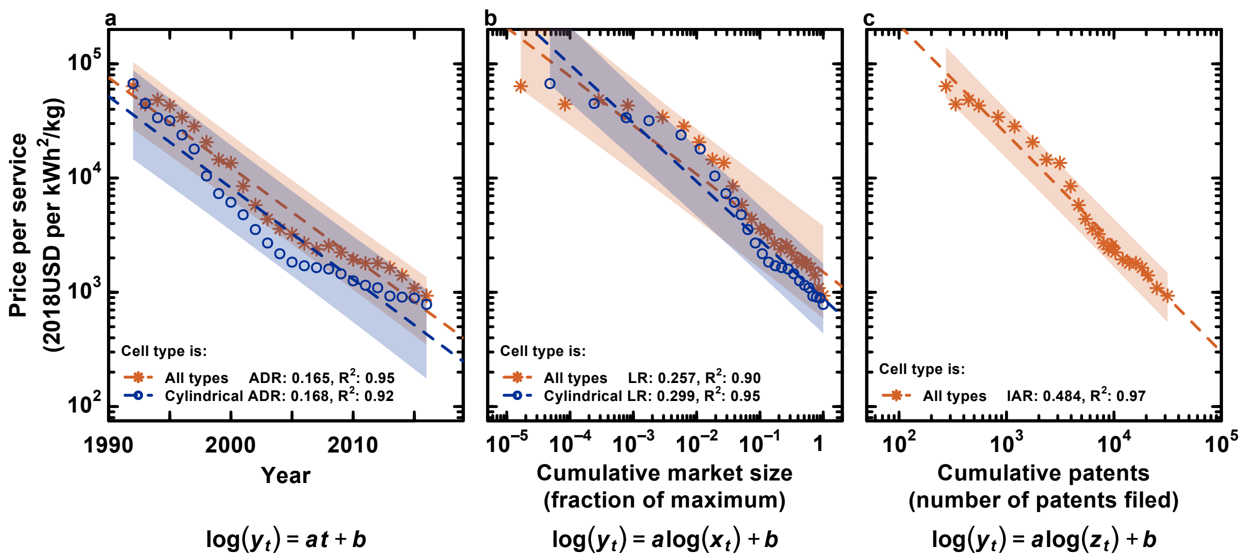


Figure S27: Lithium-ion cell price per service (in kWh^2/kg) regressed against year (a), cumulative market size (b), and cumulative patent filings (c) for all (orange asterisk marks) and cylindrical (blue circles) cells. Prediction intervals (95% level) are plotted as similarly colored shaded regions. Analyses are restricted to the years 1992 through 2016, and market size is measured in number of cells.

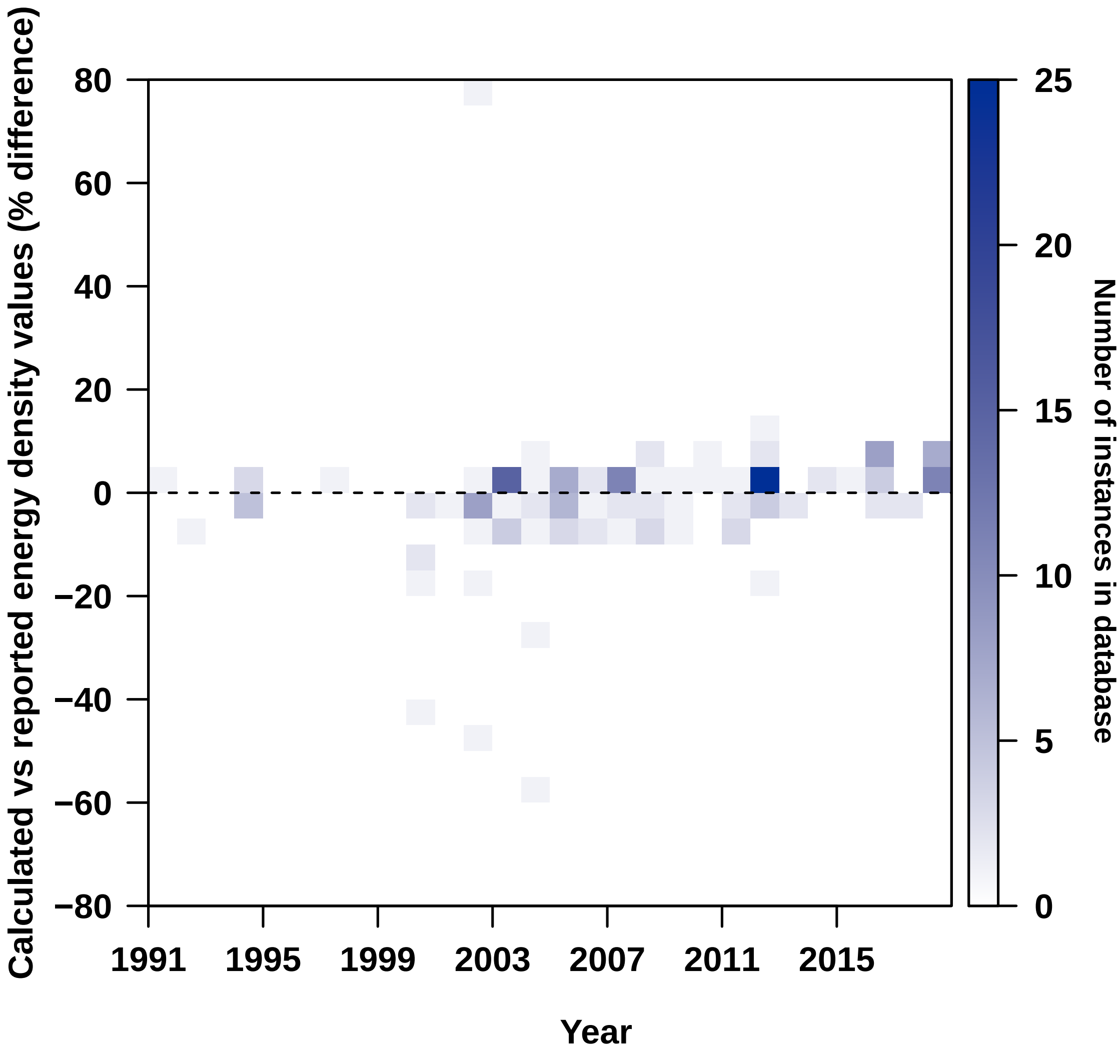


Figure S28: Difference between calculated and directly reported nameplate energy density values for commercial lithium-ion cells, between 1991 and 2018.

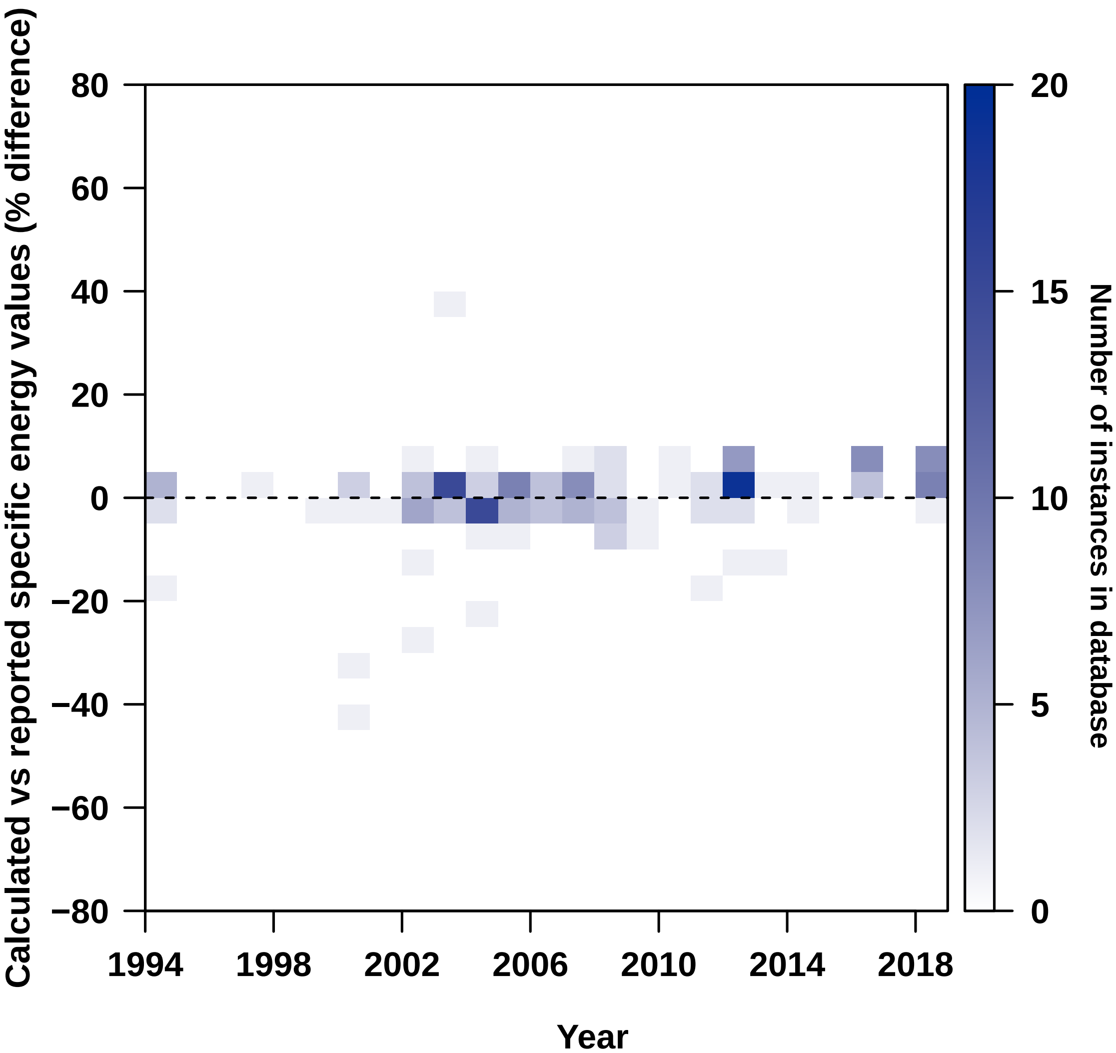


Figure S29: Difference between calculated and directly reported nameplate specific energy values for commercial lithium-ion cells, between 1994 and 2018.

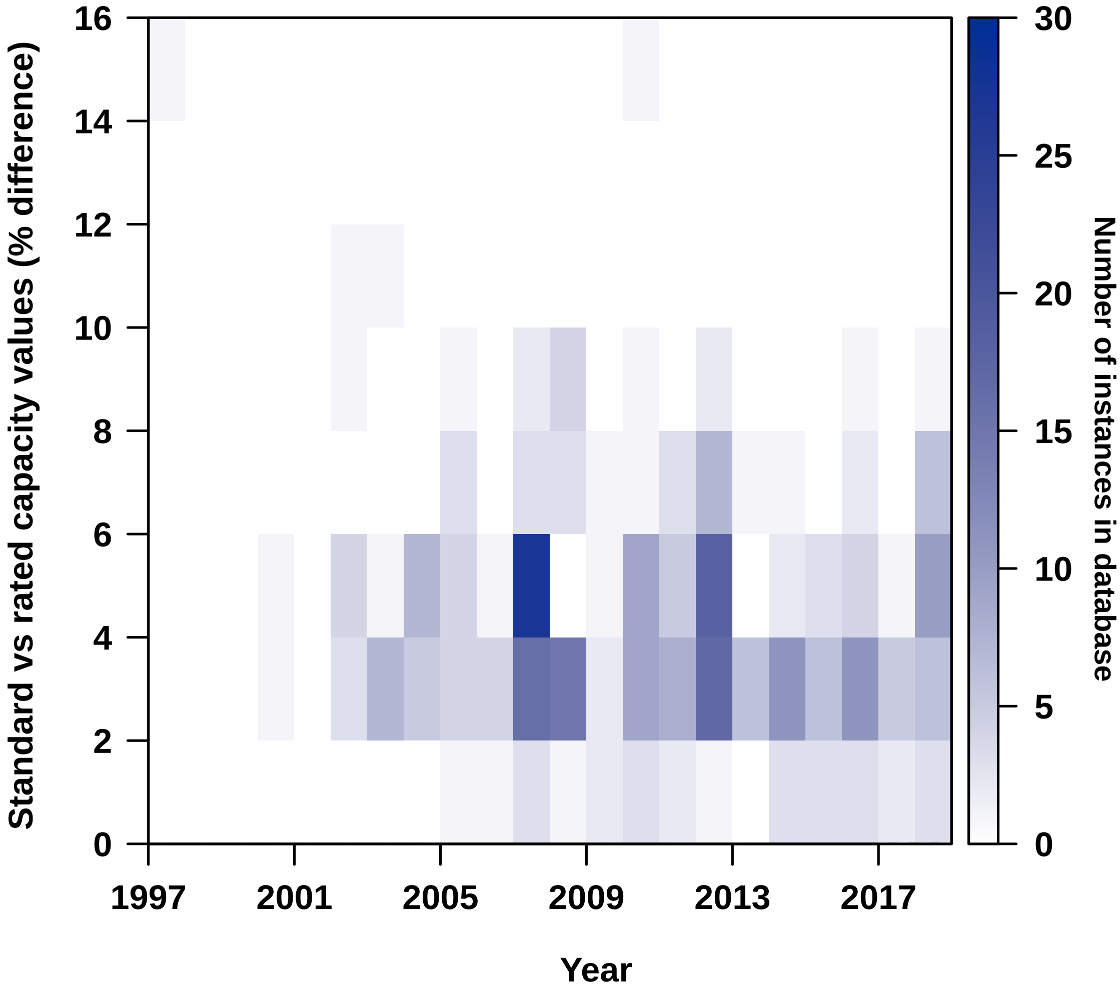


Figure S30: Difference between typical/standard and rated/minimum nameplate capacity values for commercial lithium-ion cells, between 1997 and 2018.

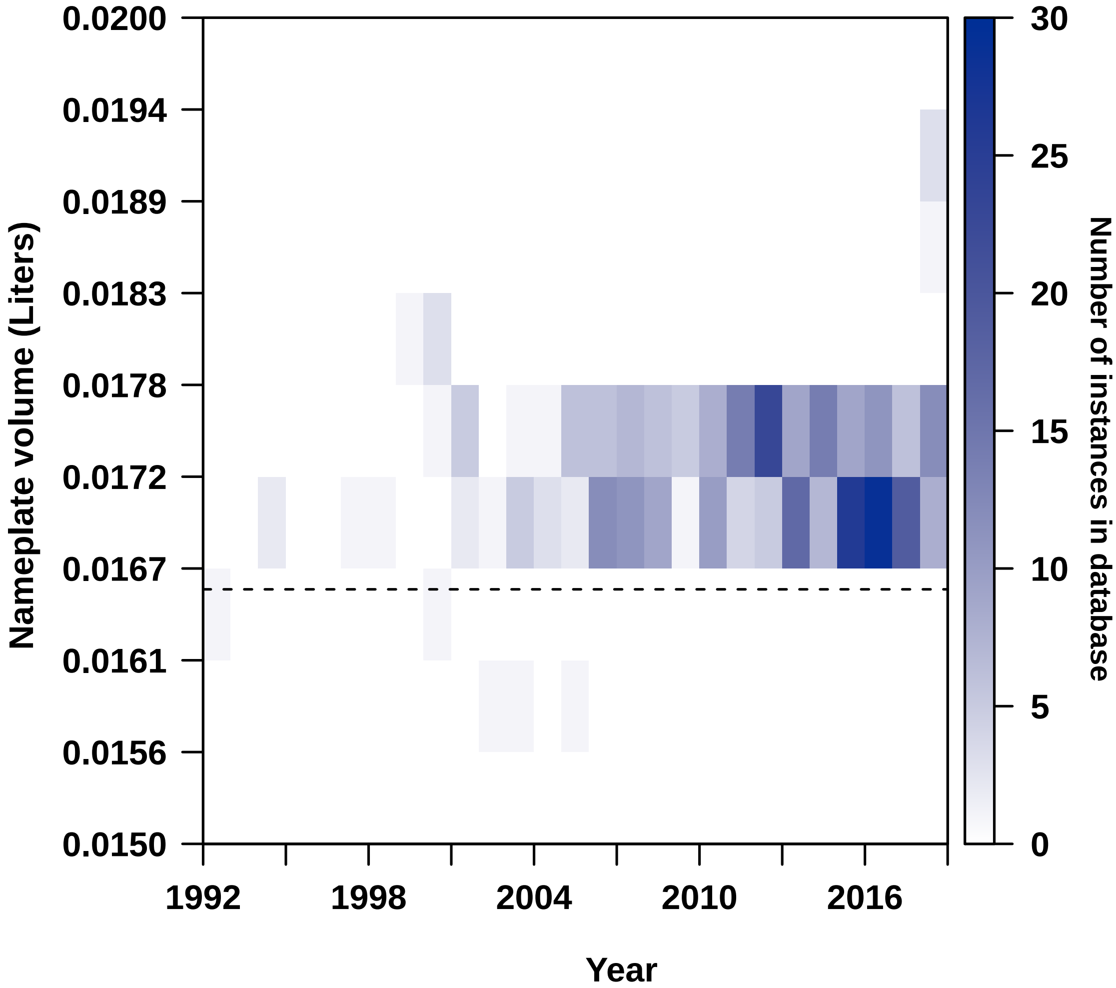


Figure S31: Nameplate volumes of commercial "18650" lithium-ion cells between 1992 and 2018. The dashed line represents the volume of a cell with a diameter of 18.00 and height of 65.00 mm.

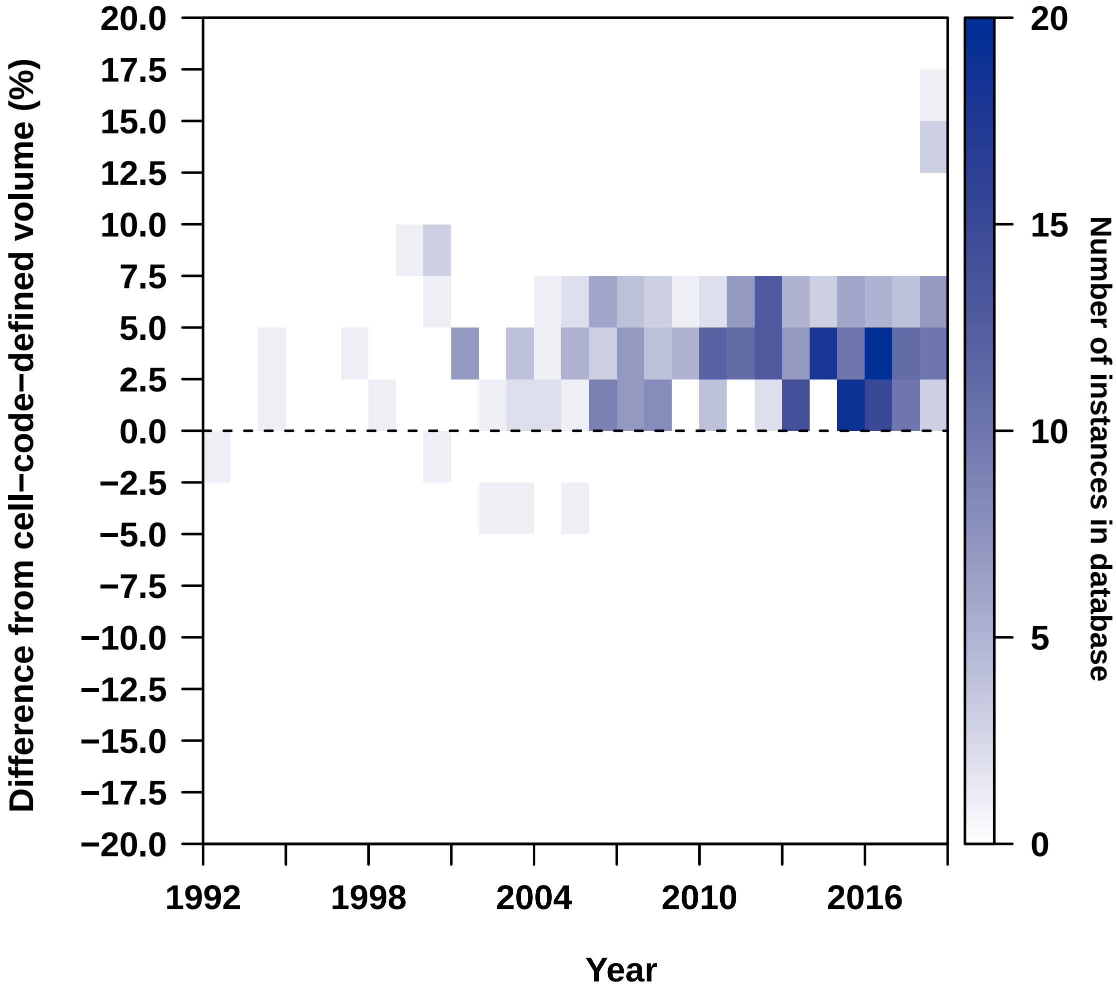


Figure S32: Difference between nameplate volumes of commercial "18650" lithium-ion cells and the volume defined by the cell code, between 1992 and 2018

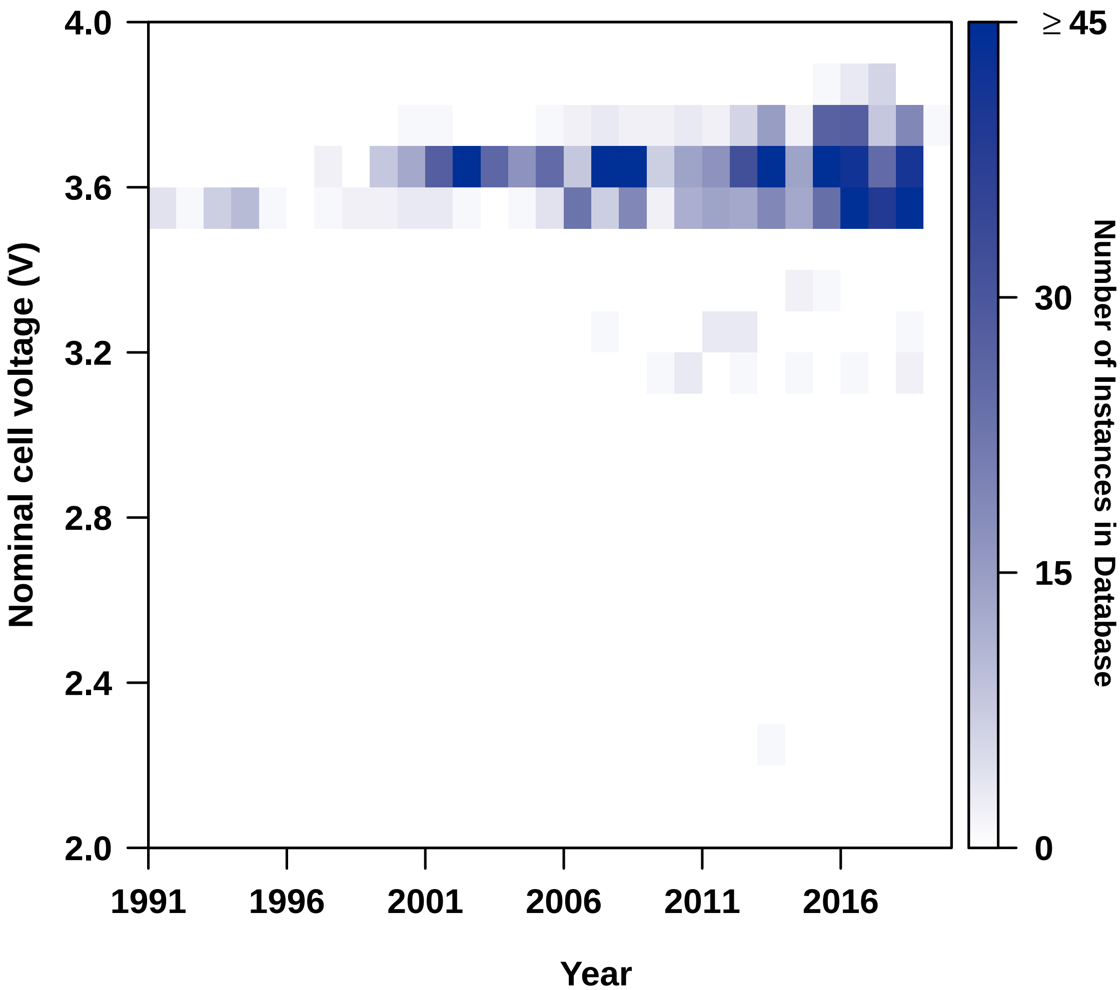


Figure S33: Nominal cell operating voltages of commercial lithium-ion cells between 1991 and 2019.

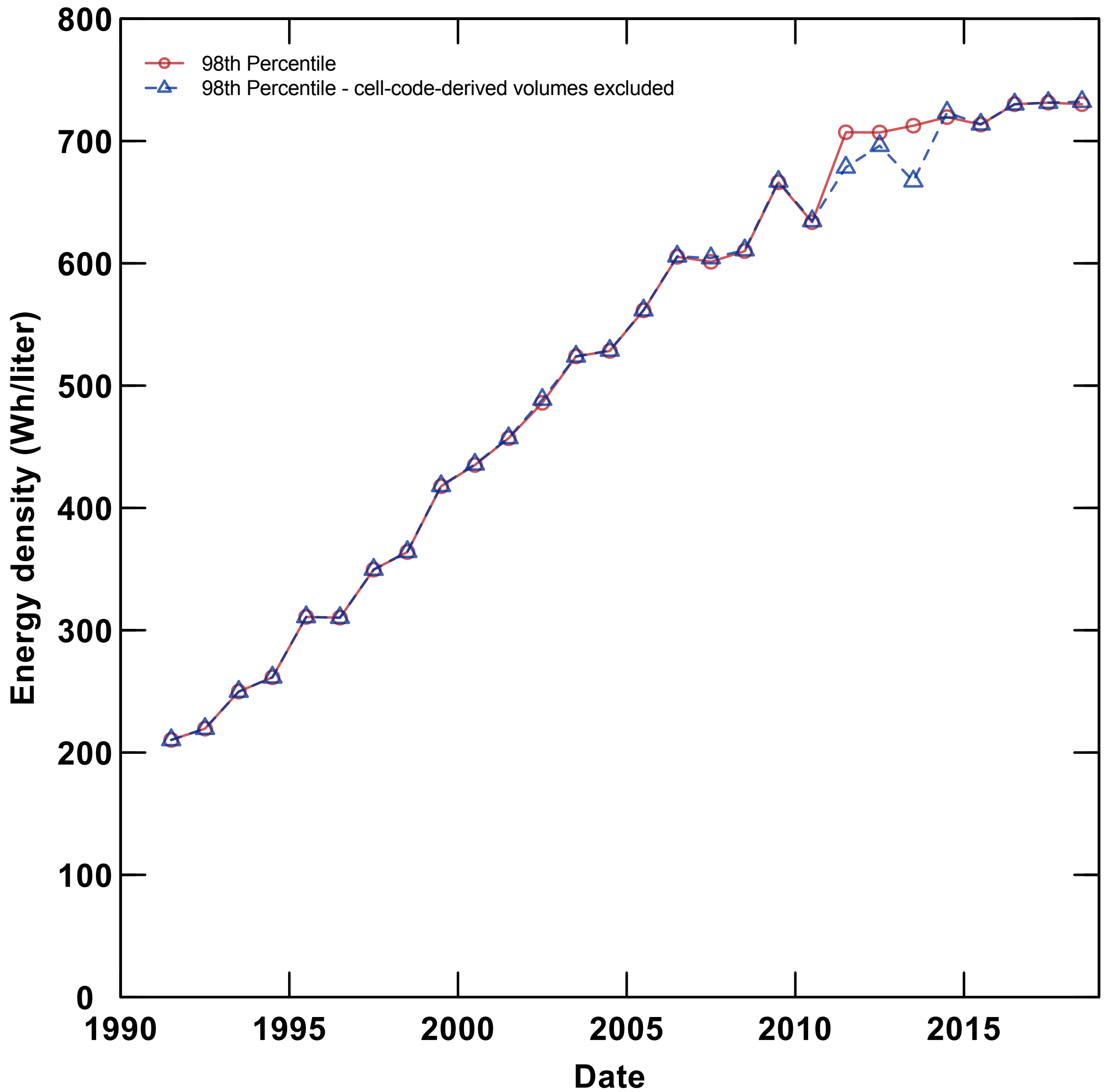


Figure S34: 98th Percentile energy density performance curves, developed with and without values calculated using cell-code-derived volumes.

5 References

(1) A. Rohatgi, *WebPlotDigitizer*, version 4.1, Automeris, 2018.

(2) K. Soetaert, *plot3D: Plotting Multi-Dimensional Data*, version 1.1.1, 2017.

(3) R. Ihaka, P. Murrell, K. Hornik, J. C. Fisher, R. Stauffer and A. Zeileis, *Colorspace: Color Space Manipulation*, version 1.3-2, 2016.

(4) Y. Shinoda, H. Tanaka, A. Akisawa and T. Kashiwagi, "Evaluation of the Plug-in Hybrid Electric Vehicle Considering Learning Curve on Battery and Power Generation Best Mix", *Electrical Engineering in Japan*, 2011, **176**, 31–40.

(5) *China Data Online*, All China Data Center, 2018, `http://chinadataonline.org/member/hym2012/hymtshowpd.asp?hy=3841&code=3841060` (visited on 08/28/2018).

(6) A. Farid, N. Anderson, J. Rosser and C. Armstrong, *Berenberg Thematics: Battery Adoption at the Tipping Point*, Berenberg, 2016, p. 24.

(7) G. E. Blomgren, Fifteenth Annual Battery Conference on Applications and Advances, Fifteenth Annual Battery Conference on Applications and Advances, IEEE, Long Beach, CA, USA, 0011–2000, pp. 97–100.

(8) M. Liebreich, "Global Trends in Clean Energy Investment", Clean Energy Ministerial.Delhi, India, 2013.

(9) L. Goldie-Scot, *A Behind the Scenes Take on Lithium-Ion Battery Prices*, Bloomberg NEF, 2019, `https://about.newenergyfinance.com/blog/behind-scenes-take-lithium-ion-battery-prices/` (visited on 03/06/2019).

(10) R. J. Brodd, Battery Technology and Fuel Cell Technology: A Retrospective, 201st ECS Meeting, The Electrochemical Society, Philadelphia, PA, 2002, vol. 2002-1.

(11) M. Broussely and G. Archdale, "Li-Ion Batteries and Portable Power Source Prospects for the Next 5–10 Years", *Journal of Power Sources*, 2004, **136**, 386–394.

(12) M. Hocking, J. Kan, P. Young, C. Terry and D. Begleiter, *Lithium 101*, GRCM2016PROD035496, Sydney, Australia, 2016.

(13) Y. Wu, *Lithium-Ion Batteries: Fundamentals and Applications*, CRC Press/Taylor and Francis, Boca Raton, FL., 2015.

(14) A. Pitt, Amitabh Arora, Robert Buckland, Willem Buiter, Peter D'Antonio, Shuang Ding, Richard Edwards, Roger Elliot, Tina M Fordham, Ian Goldin, Jeremy Hale, Keith Horowitz, Naoki Iizuka, Eric G Lee, William Lee, Tobias Levkovich, Hans Lorenzen, David Lubin, Guillaume Menuet, Edward L Morse, Richard Morse, Kiichi Murashima, Dana M Peterson, Ebrahim Rahbari, Tsubasa Sasaki,

Michael Saunders, Sofia Savvantidou, Mark Schofield, Minggao Shen, Jason Shoup, Malcolm D Spittler and Anthony Yuen, *Citi GPS: Investment Themes in 2015*, Citigroup, 2015.

(15) *Google Patents Public Data*, Google Cloud, 2019, `https://console.cloud.google.com/marketplace/details/google_patents_public_datasets/google-patents-public-data` (visited on 04/25/2019).

(16) *BigQuery*, Google Cloud, 2019, `https://cloud.google.com/bigquery/` (visited on 04/26/2019).

(17) *IPC Publication*, World Intellectual Propery Organization, 2019, `https://www.wipo.int/classifications/ipc/ipcpub/?notion=scheme&version=20190101&symbol=H01M0010052500&menulang=en&lang=en&viewmode=f&fipcpc=no&showdeleted=yes&indexes=no&headings=yes&notes=yes&direction=o2n&initial=A&cwid=none&tree=no&searchmode=smart` (visited on 04/25/2019).

(18) *Google Data Studio*, `https://datastudio.google.com` (visited on 04/26/2019).

(19) *Advanced Rechargeable Battery Market Research Program 2007*, Institute of Information Technology, Ltd., 2007.

(20) Q. Horn, *Expert Report of Quinn Horn, Ph.D, P.E.* 2016.

(21) W. Bernhart, in *Lithium-Ion Batteries*, ed. G. Pistoia, Elsevier, Amsterdam, 2014, pp. 553–565.

(22) 生駒宗久 (Munehisa Ikoma), "電池の現状と動向 (Present Situation and Trend of Batteries)", *Matsushita Technical Journal*, 2006, **52**, 8–13.

(23) N. Kittner, F. Lill and D. M. Kammen, "Energy Storage Deployment and Innovation for the Clean Energy Transition", *Nature Energy*, 2017, **2**, 17125.

(24) K. Kanamura, in *Electrochemical Science for a Sustainable Society: A Tribute to John O'M Bockris*, ed. K. Uosaki, Springer International Publishing, Cham, 2017, pp. 175–195.

(25) A. Kinoshita, "Development of Sanyo Li/Ion Batteries", 26th International Battery Seminar and Exhibit 2009.Fort Lauderdale, Florida, 2009.

(26) *Volume of Production, Shipment, Inventory, Domestic Demand and Exports*, KOSIS, Statistics Korea, 2018, `http://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1F01012&conn_path=I2&language=en` (visited on 08/27/2018).

(27) T. Mayer, D. Kreyenberg, J. Wind and F. Braun, "Feasibility Study of 2020 Target Costs for PEM Fuel Cells and Lithium-Ion Batteries: A Two-Factor Experience Curve Approach", *International Journal of Hydrogen Energy*, 2012, **37**, 14463–14474.

(28) S. Matteson and E. Williams, "Learning Dependent Subsidies for Lithium-Ion Electric Vehicle Batteries", *Technological Forecasting and Social Change*, 2015, **92**, 322–331.

(29) 機械統計年報 *(Yearbook of Machinery Statistics)*, 通商産業大臣官房調査統計部編 (Research and Statistics Department, Minister's Secretariat, Ministry of International Trade and Industry), 平成 7 年 (1995).

(30) 機械統計年報 *(Yearbook of Machinery Statistics)*, 通商産業大臣官房調査統計部編 (Research and Statistics Department, Minister's Secretariat, Ministry of International Trade and Industry), 平成 8 年 (1996).

(31) 機械統計年報 *(Yearbook of Machinery Statistics)*, 通商産業大臣官房調査統計部編 (Research and Statistics Department, Minister's Secretariat, Ministry of International Trade and Industry), 平成 9 年 (1997).

(32) 機械統計年報 *(Yearbook of Machinery Statistics)*, 通商産業大臣官房調査統計部編 (Research and Statistics Department, Minister's Secretariat, Ministry of International Trade and Industry), 平成 10 年 (1998).

(33) 機械統計年報 *(Yearbook of Machinery Statistics)*, 通商産業大臣官房調査統計部編 (Research and Statistics Department, Minister's Secretariat, Ministry of International Trade and Industry), 平成 11 年 (1999).

(34) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部編 (Research and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 12 年 (2000).

(35) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部編 (Research and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 13 年 (2001).

(36) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部編 (Research and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 14 年 (2002).

(37) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部編 (Research and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 15 年 (2003).

(38) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部編 (Research and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 16 年 (2004).

(39) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部編 (Research and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 17 年 (2005).

(40) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部 (Resarch and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 18 年 (2006).

(41) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部 (Resarch and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 19 年 (2007).

(42) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部 (Resarch and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 20 年 (2008).

(43) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部 (Resarch and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 21 年 (2009).

(44) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省経済産業政策局調査統計部 (Resarch and Statistics Department, Economic and Industrial Policy Bureau, Ministry of Economy, Trade and Industry (METI)), 平成 22 年 (2010).

(45) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 23 年 (2011).

(46) 機械統計年報 *(Yearbook of Machinery Statistics)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 24 年 (2012).

(47) 経済産業省生産動態統計年報: 機械統計編 *(Yearbook of Current Production Statistics: Machinery)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 25 年 (2013).

(48) 経済産業省生産動態統計年報: 機械統計編 *(Yearbook of Current Production Statistics: Machinery)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 26 年 (2014).

(49) 経済産業省生産動態統計年報: 機械統計編 *(Yearbook of Current Production Statistics: Machinery)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 27 年 (2015).

(50) 経済産業省生産動態統計年報: 機械統計編 *(Yearbook of Current Production Statistics: Machinery)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 28 年 (2016).

(51) 経済産業省生産動態統計年報: 機械統計編 *(Yearbook of Current Production Statistics: Machinery)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 29 年 (2017).

(52) 経済産業省生産動態統計年報: 機械統計編 *(Yearbook of Current Production Statistics: Machinery)*, 経済産業省大臣官房調査統計グループ (Research and Statistics Department, Minister's Secretariat, Ministry of Economy, Trade and Industry (METI)), 平成 30 年 (2018).

(53) D. G. Morrison, "Li-Ion Batteries Reach for Higher Performance", *Electronic Design*, 2002, **50**, 59, 60, 62, 68.

(54) *National Data*, National Bureau of Statistics of China, 2018, `http://data.stats.gov.cn/english/easyquery.htm?cn=A01` (visited on 12/13/2018).

(55) B. B. Owens and T. Osaka, "Panel Discussion Future Prospects of Lithium Batteries", *Journal of Power Sources*, 1997, **68**, 173–186.

(56) *PatSnap*, 2019, `https://analytics.patsnap.com/search/input#/classification` (visited on 04/26/2019).

(57) C. Pillot, "The Rechargeable Battery Market and Main Trends 2014-2025", 32nd International Battery Seminar & Exhibit, 2015.

(58) C. Pillot, "The Rechargeable Battery Market and Main Trends 2016-2025", 33rd International Battery Seminar & ExhibitFort Lauderdale, FL, 2017.

(59) D. MacArthur, in *Lithium Batteries: Science and Technology*, ed. G. Nazri and G. Pistoia, Springer, New York, 2003, pp. 701–706.

(60) M. Broussely, P. Biensan and B. Simon, "Lithium Insertion into Host Materials: The Key to Success for Li Ion Batteries", *Electrochimica Acta*, 1999, **45**, 3–22.

(61) H. Takeshita, "Worldwide Battery Market Status & Forecast", Power2001, 2001.

(62) G. Pistoia, *Batteries for Portable Devices*, Elsevier B.V., Amsterdam, The Netherlands, 2005.

(63) 竹下秀夫 (Hideo Takeshita), "民間蓄電池産業の現状と将来", 2006.

(64) H. Takeshita, "Worldwide Market Update on NiMH, Li Ion and Polymer Batteries for Portable Applications and HEVS", 24th International Battery Seminar & Exhibit.Fort Lauderdale, FL, 2007.

(65) M. M. Thackeray, "Spinel Electrodes for Lithium Batteries", *Journal of the American Ceramic Society*, 1999, **82**, 3347–3354.

(66) V. Srinivasan and L. Lipp, "Report on the Electrolytic Industries for the Year 2002", *J. Electrochem. Soc.*, 2003, **150**, K15–K38.

(67) R. J. Brodd, *Factors Affecting U.S. Production Decisions: Why Are There No Volume Lithium-Ion Battery Manufacturers in the United States?*, Working Paper 05–01, Economic Assessment Office, Advanced Technology Program, National Institute of Standards and Technology, 2005, p. 92.

(68) A. Yoshino, in *Lithium-Ion Batteries*, ed. G. Pistoia, Elsevier, Amsterdam, 2014, pp. 1–20.

(69) L. Gaines and R. Cuenca, *Costs of Lithium-Ion Batteries for Vehicles*, ANL/ESD-42, Argonne National Laboratory, Argonne, Illinois, 2000, p. 73.

(70) M. Doyle and P. Arora, “Report on the Electrolytic Industries for the Year 2000”, *J. Electrochem. Soc.*, 2001, **148**, K1–K41.

(71) R. J. Brodd and C. Helou, “Cost Comparison of Producing High-Performance Li-Ion Batteries in the U.S. and in China”, *Journal of Power Sources*, 2013, **231**, 293–300.

(72) D. Chung, E. Elgqvist and S. Santhanagopalan, *Automotive Lithium-Ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations*, NREL/PR--6A50--63354, Clean Energy Manufacturing Analysis Center, 2015.

(73) C. Pillot, “The Rechargeable Battery Market and Main Trends 2016-2025”, Batteries 2017Nice, France, 2017.

(74) N. Lebedeva, F. D. Persio and L. Boon-Brett, *Lithium Ion Battery Value Chain and Related Opportunities for Europe*, EUR 28534 EN, Publications Office of the European Union, Luxembourg, 2017.

(75) S. Michaelis, E. Rahimzei, A. Kampker, H. Heimes, C. Lienemann, C. Offermanns, M. Kehrer, A. Thielmann, T. Hettesheimer, C. Neef, A. Kwade, W. Haselrieder, S. Rahlfs, R. Uerlich and N. Bognar, *Roadmap: Battery Production Equipment: 2030*, VDMA Battery Production, Frankfurt, Germany, 2018.

(76) *WA's Future in the Lithium Battery Value Chain*, Chamber of Commerce and Industry WA, 2018.

(77) D. Nagelhout and J. Ros, *Elektrisch Autorijden: Evaluatie van Transities Op Basis van Systeemopties*, Planbureau voor de Leefomgeving, Bilthoven, The Netherlands, 2009.

(78) S.-i. Inage, *Prospects for Large-Scale Energy Storage in Decarbonised Power Grids*, Working Paper, OECD/IEA, Paris, France, 2009.

(79) D. L. Anderson, Master's thesis, Nicholas School of the Environment, Duke University, Durham, NC, 2009.

(80) R. Lache, D. Galves and P. Nolan, *Electric Cars: Plugged In 2*, Deutsche Bank, New York, NY, 2009.

(81) P. Sankey, D. T. Clark and S. Micheloto, *The End of the Oil Age: 2011 and beyond: A Reality Check*, Deutsche Bank, New York, NY, 2010.

(82) T. Trigg and P. Telleen, *Global EV Outlook 2013*, OECD/IEA, 2013.

(83) B. Nykvist and M. Nilsson, “Rapidly Falling Costs of Battery Packs for Electric Vehicles”, *Nature Climate Change*, 2015, **5**, 329–332.

(84) M. Liebreich, “State of the Industry Keynote”, Bloomberg New Energy Finance Summit 2015.New York, 2015.

(85) W. Schram, Master's thesis, Universiteit Utrecht, Utrecht, Netherlands, 2015.

(86) W. Hoffmann, "Importance of and Evidence for Cost Efficient Electricity Storage: Price Experience Curve for Li-Ion Batteries", Intersolar 2015.Munich, Germany, 2015.

(87) D. Sandalow, C. McCormick, T. Rowlands-Rees, A. Izadi-Najafabadi and I. Orlandi, *Distrubuted Solar and Storage - ICEF ROADMAP 1.0*, Innovation for Cool Earth Forum and Bloomberg New Energy Finance, 2015, p. 66.

(88) C. Curry, *Lithium-Ion Battery Costs and Market*, Bloomberg New Energy Finance, 2017.

(89) M. B. Lieberman, "The Learning Curve and Pricing in the Chemical Processing Industries", *The RAND Journal of Economics*, 1984, **15**, 213–228.

(90) G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke and J. Van Mierlo, "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030", *Energies*, 2017, **10**, 1314.

(91) O. Schmidt, A. Hawkes, A. Gambhir and I. Staffell, "The Future Cost of Electrical Energy Storage Based on Experience Rates", *Nature Energy*, 2017, **2**, 17110.

(92) O. Schmidt, S. Melchior, A. Hawkes and I. Staffell, "Projecting the Future Levelized Cost of Electricity Storage Technologies", *Joule*, 2019, **3**, 81–100.

(93) I.-Y. L. Hsieh, M. S. Pan, Y.-M. Chiang and W. H. Green, "Learning Only Buys You so Much: Practical Limits on Battery Price Reduction", *Applied Energy*, 2019, **239**, 218–224.