Appendix E

Battery Cost for Heavy-Duty Electric Vehicles

Table of Contents

List of Figures

This discussion document is a summary of a literature review of available information to answer questions from the Innovative Clean Transit Workgroup about heavy duty battery costs and their projections. Battery cost projections can be used to estimate the impact on future bus prices and to estimate the costs of future battery mid-life replacements where applicable. This document was first released to the public in August 2016 and revised in August 2017 with errata shown in the last page. It is available at https://www.arb.ca.gov/msprog/bus/battery_cost.pdf. This appendix also contains the revision made in August 2017 and other minor changes from the original posting.

A. Electric Vehicle Batteries

Batteries are the most significant cost component for a battery electric vehicle (BEV). Lithium-ion batteries are currently the battery choice for light- and heavy-duty BEVs and are widely available commercially; however, there are multiple lithium-ion battery chemistries that are used in different heavy-duty applications. This paper summarizes available information from published studies that relate to questions about battery cost projections.

Battery requirements for heavy-duty BEVs are different from those for light-duty ones, due to different weights, life expectancy, and driving cycles. Compared with light-duty vehicles, heavy-duty vehicles are heavier, need more horsepower, have greater expected lifetime mileages, and require more demanding duty cycles, which vary widely. For example, urban transit buses incorporate a lot of stop-and-go driving with low average speed, while long-haul trucks make few stops, maintains a relatively constant speed, and requires high power for long period of grade climbing. Differences between heavy-duty and light-duty vehicles also result in different battery requirements in power, energy, and life span[1]. Though batteries for heavy-duty BEVs sometimes use similar battery chemistry as light duty ones, they are packaged differently and are not produced or purchased in high volumes like they are for light-duty vehicles.

Most of the studies with battery cost estimates are for all types of lithium-ion batteries lumped into one group, without distinguishing specifics chemistries. However, it is important to understand the battery chemistry because of differences in material costs, technology maturity, production volume, which are crucial factors influencing battery cost. Data limitations of current studies make it challenging to estimate projections for specific chemistries of lithium-ion batteries for heavy-duty vehicle applications like transit buses, but the studies can be used to estimate general battery price trends for heavy duty vehicles and likely battery cost reductions.

[1] National Research Council (2012), Review of the 21st Century Truck Partnership, Second Report. Available: http://nap.edu/13288.

The purpose of this discussion paper is to provide a literature review and overview of battery cost for heavy-duty BEVs with a focus on buses. The following questions are discussed:

1. What are the major chemistries for batteries in buses?
2. What are the driving factors for battery cost?
3. What are the limitations of current cost studies?
4. What are the best estimates of battery cost at the present and in the future?

B. Background on Lithium-ion Battery Chemistries

There are a variety of lithium-ion chemistries with trade-offs for each. Table 1 shows a variety of lithium-ion chemistries with their associated specific energy densities and existing applications[2,3,4].

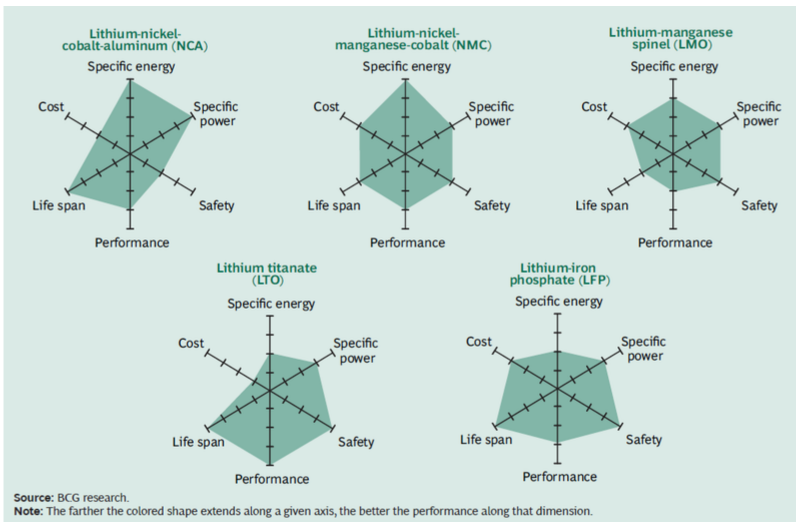
Table 1: Lithium-ion Battery Chemistry Characteristics and Applications

Battery Chemistries	Specific Energy (Wh/kg)	Life span (cycles)	Applications
Nickel Cobalt Aluminum (NCA)	160	2000+	Used in cars (e.g., Toyota Prius plug-in hybrid, Tesla)
Nickel Manganese Cobalt Oxide (NMC)	150	2000+	Used in consumer goods, cars, and buses(e.g., Nissan Leaf, Chevrolet Bolt, Proterra, New Flyer)
Lithium Manganese Oxide (LMO)	150	1500+	Used in cars; most LMO blends with NMC to improve the specific energy and prolong the life span (e.g. Nissan Leaf)
Lithium Titanate (LTO)	90	5000+	Used in cars and buses (e.g., Honda Fit, Proterra)
Lithium Iron Phosphate (LFP)	140	5000+	Used in cars, buses, and trucks (e.g., BYD, TransPower, Siemens, Nova Bus, Volvo) and stationary energy storage systems

[2] California Air Resources Board (CARB) (2015), Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses, October 2015. Available: www.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf.
[3] Element Energy (2012), Cost and Performance of EV Batteries: Final Report for the Committee on Climate Change, March 21, 2012. Available: www.element-energy.co.uk/wordpress/wp-content/uploads/2012/06/CCC-battery-cost_-Element-Energy-report_March2012_Finalbis.pdf.
[4] Battery University (2016), Safety of Lithium-ion Batteries, Last Updated August 10, 2016. Available: http://batteryuniversity.com/learn/article/safety_of_lithium_ion_batteries.

Boston Consulting Group (BCG) (2010)[5] identified six key battery characteristics: safety, life span (measured in terms of both number of charge/discharge cycles, and overall battery age), performance (peak power at low temperatures, state-of-charge measurement, and thermal management), specific energy (the nominal battery energy per unit mass), specific power (the maximum available power per unit mass), and battery cost. The results are shown in Figure 1. Each technology has its advantages and disadvantages when considering all six dimensions. It is important to note that when analyzing this figure, the farther the shape extends along a given axis, the better the performance is in the dimension. As an example, LTO is generally more expensive than LFP batteries but provide better performance.

Figure 1: Trade-offs Among Different Lithium-ion Batteries



Source: BCG (2010)

C. Batteries for Heavy-Duty Applications

Three types of batteries, LFP, LTO, and NMC, show promise in the application of medium- and heavy-duty vehicles[2,6,7] due to the strengths of long life span, high power and specific energy, and high safety performance.

LFP batteries use graphite as the anode, and lithium iron phosphate ($LiFePO_4$) as the cathode. The electrolyte is a lithium salt in an organic solvent. In addition, the use of phosphate as a positive electrode significantly reduces the potential for thermal

[5] Boston Consulting Group (BCG) (2010), Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020. Available: www.bcg.com/documents/file36615.pdf.
[6] Navigant Research (2014), The Lithium Ion Battery Market: Supply and Demand. ARPA E RANGE Conference, January 28, 2014. Available: www.arpa-e.energy.gov/sites/default/files/documents/files/Jaffe_RANGE_Kickoff_2014.pdf.
[7] BYD (2016), Personal Communication with Michael Austin, Vice President of BYD America, on March 9, 2016.

runaway. These batteries are typically good for many cycles, with BYD claiming up to 7,200 charge/discharge cycles, corresponding to nearly 20 years if cycled once daily, to degrade the battery to 80 percent of its original capacity. LFP is one of the selections for a high power density lithium battery. It means that LFP has higher discharge current and requires smaller battery size to achieve a given performance target, which is important for the vocational application that requires space for its payload. In addition, LFP has a superior thermal and chemical stability, which provides better safety[8]. According to energy storage-related patent activity from 1999 through 2008, LFP technology has been the focus of at least twice as much innovation as LTO technology, and four times as much as NMC technology. This battery technology is used in the TransPower BEV drayage truck and electric school bus demonstrations. BYD uses self-developed "fire safe" iron phosphate batteries on their electric buses.

LTO batteries use lithium titanate as the anode, and usually manganese-based material as the cathode. They use a non-aqueous electrolyte. LTO battery has the advantage of being faster to charge than other lithium-ion batteries[9], because of lower ratio of heating energy during charging and higher fraction of the Ah capacity that could be returned without current taper, yet it is more expensive. The battery has a long life span and some models have been reported to be more than 10,000 cycles at 80 percent depth of discharge[10]. While the energy density is lower than other lithium-ion batteries, they can be safely operated over a wide discharge range, so the effective available energy is comparable to LFP batteries. LTO batteries are used on the Proterra electric fast charging buses.

NMC is another type of lithium-ion battery that shows promise in electric buses. These batteries have a better specific energy and longer lives compared to many other lithium-ion approaches. The increased energy can contribute to a longer range. For the same range, this chemistry allows the battery pack to be lighter and take up less space. Compared with LFP, NMC has lower safety level, yet IDTechEx Research predicted that NMC suppliers would search advanced battery management systems to match LFP's safety levels and create superior batteries. This battery chemistry has been widely used in many light-duty plug-in electric vehicles such as the Nissan Leaf, Chevrolet Volt, Chevrolet Spark EV, and Hyundai Sonata plug-in hybrid electric vehicle. It also has

[8] IDTechEx (2016), Electric Bus Sector is Game Changer for Battery Market, March 04, 2016. Available: http://www.idtechex.com/research/articles/electric-bus-sector-is-game-changer-for-battery-market-00009175.asp.

[9] CACTUS (2015), Models and Methods for the Evaluation and Optimal Application of Battery Charging and Switching Technologies for Electric Busses. Available: http://www.cactus-emobility.eu/CACTUS_Deliverable_1.2_Technologies-to-enable-fully-electric-busses.pdf.

[10] NEI Corporation, Lithium Titanate Based Batteries for High Rate and High Cycle Life Applications. Available: http://neicorporation.com/white-papers/NEI_White_Paper_LTO.pdf.

been used on New Flyer's Xcelsior XE40 electric transit bus and Proterra's extended-range electric buses.

D. Factors Contributing to Battery Cost

There are several factors driving battery cost. Battery costs varies with different combinations of alternative chemistries, electrode designs, packing alternatives, capacities of individual cells, as well as pack configuration, thermal management, and control electronics which make up the pack[11]. The Electric Power Research Institute (EPRI) identified three key cost dependencies, which are cell size, cell production volume, and standardization of battery components, based on a review of seven most used battery cost models[12]. Studies from Argonne National Laboratory (ANL) noted that estimates of battery costs vary considerably with different power to energy (P/E) ratio, production sale, and thermal management systems[13,14]. For a future outlook, technological improvements in higher energy density of lithium cells, less expensive cell material, and more efficient manufacturing process are expected to reduce battery costs[15].

BCG (2010) further identified the value chain of EV batteries which consists of seven steps, including component production (including raw material), cell production, module production, assembly of modules into the battery pack (including an electronic control unit and a cooling system), integration of the battery pack into the vehicle, use during the life of the vehicle, and reuse and recycling[5]. Most studies about battery costs focus on the first four steps which make up the manufacture of battery packs. For a specific battery, its cost reduction depends heavily on increasing production volume, which can be achieved by rise of demand, industry experience, and increasing automation.

While most projections only estimate cost without describing production volume, or use a single volume production in their estimates, volume effects should be considered as there is an expected change in production volume per plant with time[3]. Models have

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[11] Sakti, A. S., Michalek, J. J. , Fuchs, E. R. H., and Whitacre, J. F. (2015), A Techno-Economic Analysis and Optimization of Li-Ion Batteries for Light-Duty Passenger Vehicle Electrification, Journal of Power Sources, 273, 966–980, https://doi.org/10.1016/j.jpowsour.2014.09.078.

[12] Electric Power Research Institute (EPRI) (2010), Large-Format Lithium-ion Battery Costs Analysis: Critical Review of Existing PHEV Lithium Ion Battery Cost Studies, December 2010. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001019923.

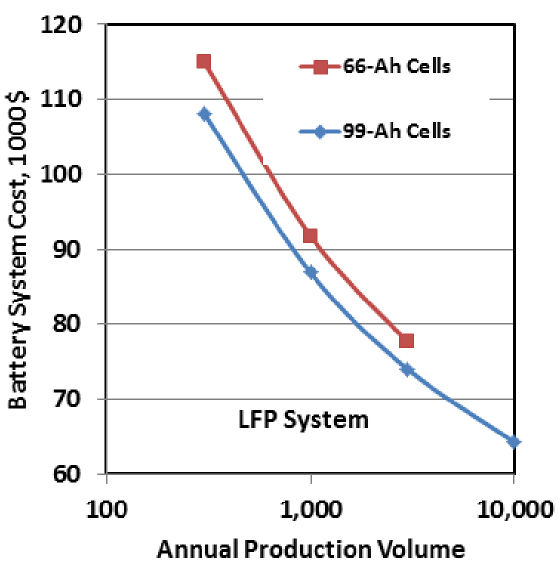
[13] Nelson, P. A., Santini, D. J., and Barnes, J. (2009), Factors determining costs of lithium-ion batteries for PHEVs, EVS24, Savanger, Norway, May 13-16, 2009. Available: http://www.cars21.com/web/assets/link/EVS-24-3550250%20santini.pdf.

[14] Miller, J. F. (2010), Analysis of current and projected battery manufacturing costs of electric, hybrid, and plug-in hybrid electric vehicle, EVS25, Shenzhen, China, November 5-9, 2010. Available: http://www.evs24.org/wevajournal/php/download.php?f=vol4/WEVA4-4050.pdf.

[15] Edison Electric Institute (EEI) (2014), Transportation Electrification: Utility Fleets Leading the Charge, June 2014. Available: http://www.eei.org/issuesandpolicy/electrictransportation/fleetvehicles/documents/eei_utilityfleetsleadingthecharge.pdf.

been developed to estimate cost and performance of battery packs[3]. BatPac model[16] is one of them. BatPac model uses a bottom up approach of cell design, as well as the links between production costs, cell design, and volume. Designs of a battery with specified power, energy, and type of vehicle battery (PHEV or EV) are used as input of this model. The cost of the designed battery is then calculated by accounting for every step in the lithium-ion battery manufacturing process. The assumed annual production level directly affects each process step. The total cost to the original equipment manufacturer calculated by the model includes the materials, manufacturing, and warranty costs. BatPac model assumes a highly optimized manufacturing plant built for production in 2020 to provide for a consolidated EV market. This model was designed to estimate the cost of batteries manufacturing in large quantities at a plant specifically designed to only produce those batteries. Paul Nelson and Shabbir Ahmed, scientists at ANL[17], provided a demonstration of how battery cost decline with the increase of batteries produced, using a 324 kWh (3 packs) LFP battery in a case study, as shown in Figure 2. This example is given to provide an indication of the effect of production volume on the cost, and it is not intended to predict cost of a specific battery design. A cost reduction of 41 percent is shown if the production volume increases from 300 battery systems to 10,000 battery systems per year.

Figure 2: Cost Dependence on Battery Production Volume with Assumptions



Cell Chemistry:	LFP/graphite	
	Large Cells	Small Cells
Number of packs in parallel	3	3
Cells per pack	336	504
Cell capacity, Ah	99	66
Number of cells in parallel	2	3
Nominal battery voltage, V	551	551
Pack power, kW	133.3	133.3
Total pack energy, kWh	108	108
Useable battery energy, % of total	85	85
% OCV at full power	97.1	97.2
Bus energy requirement, Wh/mile	1,775	1,775
Pack dimensions, mm		
Length	1,647	2,425
Width	1,740	1,457
Height	169	147
Battery weight (3 packs), kg	2,525	2,636
Battery volume (3 packs), L	1,474	1,579

[16] Argonne National Laboratory (2012), Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Second Edition, ANL-12/55, December 2012. Available: http://www.cse.anl.gov/batpac/files/BatPaC%20ANL-12_55.pdf.
[17] Argonne National Laboratory (2016), Email Communication with Paul Nelson and Shabbir Ahmed, Chemical Engineers, on May 5, 2016.

Source: Argonne BatPac Model

Research work around the world is examining other potential technologies that can yield higher energy density and/or lower cost per unit of energy. None of these more futuristic battery systems has achieved enough maturity to become commercial yet. Solid-state lithium-ion batteries use solid electrolytes, instead of conventional liquid ones. Solid electrolyte could not only increase battery life, but also storage capacity and safety, as liquid electrolytes are the leading cause of battery fire[18,19, 20]. Lithium-silicon batteries employ a new type of silicon anode that would be used in place of a conventional graphite anode. The silicon anode has a theoretical specific capacity ten times more than that of anodes such as graphite, while it swells to more than three times its volume when fully charged and this swelling quickly breaks the electrical contacts in the anode[21]. Tesla has taken a step by shifting the cell chemistry for Model S' updated battery pack, which provides a 6% increase in range, to partially use silicon in the anode[22]. Lithium-sulfur chemistry utilizes a lithium metal anode and a cathode based on sulfur compounds. This system could theoretically double the specific energy of lithium-ion batteries and offer a competitive cost. Lithium-air battery utilizes lithium-metal anodes and an air electrode so that the cathodic active material, oxygen, is taken from the air and at the charged state does not add to the weight of the battery. However, National Research Council (NRC)[23] predicts that even if these new technologies can be successfully developed, they probably will not be widely available soon. Besides, the scale-up and mass production of batteries from research laboratory to market is slow[24]. Therefore, potential cost reductions achieved by new technologies are not considered in this discussion paper.

[18] Tan, G., Wu, F., Zhan, C., Wang, J., Mu, D., Lu, J., and Amine, K.(2016), Solid-State Li-Ion Batteries Using Fast, Stable, Glassy Nanocomposite Electrolytes for Good Safety and Long Cycle-Life, Nano Letter, 16 (3), 1960-1968, DOI: 10.1021/acs.nanolett.5b0

[19] Wang, Y., Richards, W.D., Ong, S.P., Miara, L.J., Kim, J.C., Mo, Y., and Ceder, G. (2015), Design Principles for Solid-State Lithium Superionic Conductors, Nature Materials, 14, 1026–1031. Available: https://doi.org/10.1038/nmat4369.

[20] MIT News (2015), Going Solid-State Could Make Batteries Safer and Longer-Lasting, August 17, 2015. Available:: http://news.mit.edu/2015/solid-state-rechargeable-batteries-safer-longer-lasting-0817.

[21] Hassan, F.M., Batmaz, R., Li, J., Wang, X., Xiao, X., Yu, A., and Chen, Z. (2015), Evidence of Covalent Synergy in Silicon-Sulfur-Graphene Yielding Highly Efficient and Long-Life Lithium-Ion Batteries, Nature Communications, doi:10.1038/ncomms9597.

[22] Christian Ruoff (2015), Tesla Tweaks Its Battery Chemistry: A Closer Look at Silicon Anode Development, September 23, 2015. Available: https://chargedevs.com/features/tesla-tweaks-its-battery-chemistry-a-closer-look-at-silicon-anode-development/.

[23] National Research Council (NRC) (2013), Transitions to Alternative Vehicles and Fuels. Available: http://nap.edu/18264.

[24] Venkat Srinivasan (2015), The Future of (Electrochemical) Energy Storage, Lawrence Berkeley National Lab, April 22, 2015. Available: https://www.arb.ca.gov/research/seminars/srinivasan/srinivasan.pdf.

E. Battery Cost Estimates

Battery costs for light-duty BEVs has been declining rapidly during the last 10 years, and similar trends are expected for heavy-duty batteries especially with increasing heavy-duty BEV deployment. Although some batteries used for heavy-duty electric vehicles share similar chemistry as light-duty ones, battery pack costs per kWh for heavy-duty BEVs are currently higher, mainly because of different packaging, thermal management systems, and lower purchase volumes.

Currently, it is somewhat challenging to estimate battery cost for heavy-duty BEVs due to the following three reasons: (1) battery costs vary widely with chemistry, yet most estimates are for all types of lithium-ion batteries lumped into one group; (2) most published estimates are applicable for light-duty BEVs and not for heavy duty vehicle applications; and (3) there is lack of information about explicit relationships between production volume and battery cost for heavy duty vehicle applications. However, the estimated costs from various studies can be used as a reference to project the trend of battery costs over time.

We evaluated battery cost ranges from different literature sources. The following studies were reviewed and considered for the estimates of battery costs that might be applicable to transit buses, including CE Delft (2013)[25], CACTUS (2015)[9], CALSTART (2012)[26], Rocky Mountain Institute (RMI) (2015)[27], Navigant Research (2014)[6], and cost estimates from OEMs [28, 29,30], as summarized in Table 2. Studies by BCG (2010)[5] and Nykvist and Nisson(2015)[31] are discussed as well, since they provide insight about changes of battery cost over time. However, these two studies are not used for the final cost estimates because they focus more on batteries for light-duty BEVs. All the references shown in Table 2 were chosen, because they have either specified battery chemistry and/or application, or systematically integrated information from studies.

[25] CE Delft (2013), Zero Emissions Trucks: An Overview of State-of-the-Art Technologies and Their Potential, July 2013. Available: http://www.theicct.org/sites/default/files/publications/CE_Delft_4841_Zero_emissions_trucks_Def.pdf.

[26] CALSTART (2012), Best Fleet Uses, Key Challenges and the Early Business Case For E-Trucks: Findings and Recommendations of the E-Truck Task Force. Available: http://www.calstart.org/Libraries/E-Truck_Task_Force_Documents/Best_Fleet_Uses_Key_Challenges_and_the_Early_Business_Case_for_E-Trucks_Findings_and_Recommendations_of_the_E-Truck_Task_Force.sflb.ashx.

[27] Rocky Mountain Institute (2015), The Economics of Load Defection: How Grid-Connected Solar-Plus-Battery Systems Will Compete with Traditional Electric Service, Why It Matters, and Possible Paths Forward, April 2015. Available: https://rmi.org/insight/economics-load-defection/.

[28] New Flyer (2016), Email Communication with David Warren, Director of Sustainable Transportation, on June 13, 2016.

[29] Proterra (2016), email communication with Dustin Grace, Director of Battery Engineering, June 9, 2016.

[30] Transit Agency Subcommittee (2016), Email and Personal Communications with Cost Subgroup, Steven Miller, Director of Maintenance at Golden Gate Bridge, Highway and Transportation District.

[31] Nykvist, B. and Nilsson M. (2015), Rapidly Falling Costs of Battery Packs for Electric Vehicles, Nature Climate Change, doi: 10.1038/NCLIMATE2564.

Table 2: Battery Cost Estimates and Projections from Different Sources

Reference	Chemistry	Application	Cost Estimates and Projection [a]
CE Delft (2013)[b]	Not Specified	Distribution and long haul trucks	$600/kWh (2012); $320/kWh (2020); $210/kWh (2030)
CACTUS (2015)	LFP	Not Specified	$350/kWh (2015)
	LTO	Not Specified	$2000/kWh (2015)
CALSTART (2012)	Not Specified	Trucks	$500-600/kWh (2015); 450/kWh (2020); $300/kWh (2025)
Rocky Mountain Institute (2015)[c]	Not Specified	Residential and commercial battery storage system	$540/kWh (2015); $405/kWh (2020); $225/kWh (2030); $200/kWh (2040)
Boston Consulting Group (2012)	NCA	Not Specified	$990-$1220/kWh (2009); $360-$440/kWh (2020)
Navigant Research (2014)	LFP	Not Specified	$400-$1200/kWh (2014)
	LTO	Not Specified	$800-$2000/kWh (2014)
	NMC	Not Specified	$700-$900/kWh (2014)
Nykvist and Nisson (2015)[d]	Not Specified	Not Specified	Whole industry: $410/kWh(2015); Market leader: $300/kWh (2015)
BYD (2016)	LFP	Buses (depot charging)	$900/kWh (2016); $600/kWh (2025)[e]
Proterra (2016)	LTO	Buses (on-route charging)	Upwards of $1000/kWh (2016); $700/kWh (2022)[f]
New Flyer (2016)	NMC	Buses (depot charging)	$750-$850/kWh (2016)[g]
ACTIA(2016)	LTO	Buses (on-route charging)	$1500-$2000/kWh (2016)[h]
	Not Specified	Buses (depot charging)	$750-$1000/kWh (2016)[h]

a Original data from references; not adjusted by CPI.
b A Euro to US exchange rate of 1.33 was used to convert the cost from $€_{2010}$.
c Average value used for analysis in the report; based on various studies.
d Cost estimates from this paper are based on 85 references, including peer reviewed papers in international scientific journals, the most cited grey literature (e.g. estimates from agencies, consultancy and industry analysts), news items of individual accounts from industry representatives and experts, and some further novel estimates for leading BEV manufactures.
e Rough estimate derived from bus price information reflecting the assumption that the price difference between BYD's 40 foot bus price and a conventional diesel bus price in 2016 is primarily from the battery cost as described in section E.4.
f Based on discussion with Dustin Grace, Director of Battery Engineering of Proterra, as described in section E.4.
g Based on discussion with David Warren, Director of Sustainable Transportation of New Flyer, as described in E.4
h Based on ACTIA's presentation and discussion with Greg Fritz, EV Business Unit Manager of ACTIA.

1. CE Delft

CE Delft (2013)[25] stated that future costs are difficult to predict, but estimated that battery costs will decrease due to effects on production volume as well as introducing new technologies. This report assumed that the battery system cost for both light- and heavy-duty battery electric vehicles as well as for the battery used by fuel cell electric vehicles to be equivalent. Cost ranges in this report have been determined with different literature sources, most of which rely on studies for light-duty BEVs, including McKinsey[32], ICF[33], Howell[34], Element Energy[3], and Roland Berger[35], and implicated rising production rates of up to 100,000 units as well as continual increasing of future investments. They estimated that the battery systems cost $600/kWh in 2012, $320/kWh in 2020, and $210/kWh in 2030 (all costs are shown in 2010 dollars, and a Euro to US exchange rate of 1.33 was used to convert from Euro). The projection estimates a 7.6 percent and 3.9 percent annual reduction from 2012 to 2020 and 2020 to 2030, respectively.

2. Boston Consulting Group

BCG (2010) presented a case study of battery cost analysis. They assumed a typical supplier of 15 kWh NCA batteries, which generally apply to light-duty vehicles such as plug-in Prius, using modestly automated production to make 50,000 cells and highly manual assembly to produce 500 battery packs in 2009. It was estimated that the costs to an OEM would range from $990 to $1220/kWh, and this price will decrease by roughly 60 to 65 percent from 2009 to 2020, that is 8-9 percent annually, resulting a price of $360-$440/kWh with the annual production of 73 million cells and 1.1 million batteries in 2020. This study provides a conceptual idea about how NCA battery cost changes with annual production, but is applicable to light-duty BEV production volumes.

3. Nykvist and Nilsson

Nykvist and Nilsson (2015) presented cost estimates of all variants of lithium-ion technology used for BEVs, shown in Figure 3, as the aim is to track the progress of BEV technology in general and data is too scarce for individual lithium-ion cell chemistry variants. They evaluated that the average estimated battery cost for the industry as a whole declined by 14 percent annually from 2007 to 2014, and costs for market-leading manufacturers declined by 8 percent annually for the same period, leading to an

[32] McKinsey (2012), Urban Buses: Alternative Powertrains for Europe, A Fact-Based Analysis of the Role of Diesel Hybrid, Hydrogen Fuel Cell, Trolley and Battery Electric Powertrains, June 12, 2012. Available: https://www.fch.europa.eu/node/790.

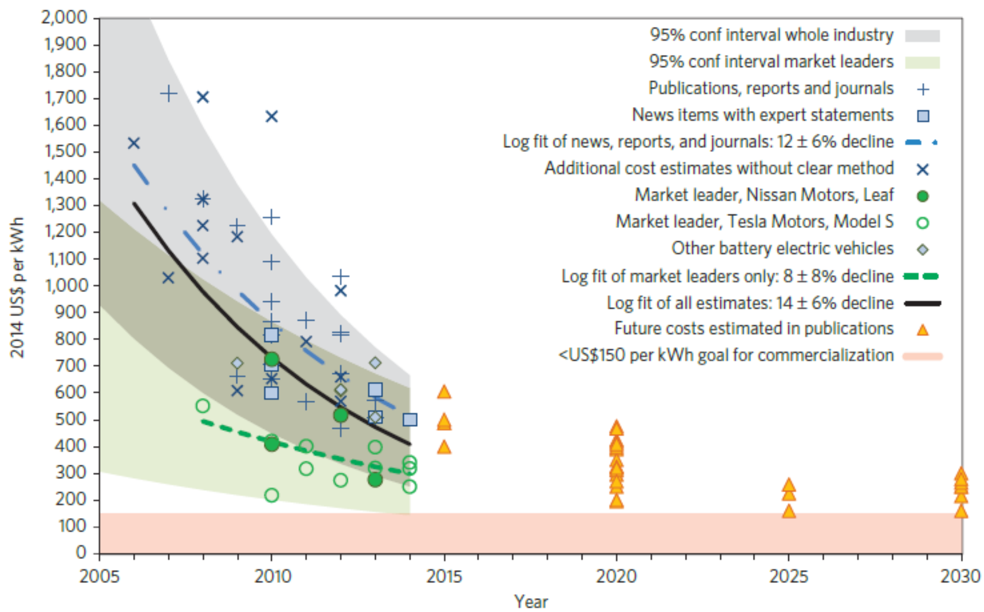
[33] ICF (2011), Impacts of Electric Vehicles – Deliverable 2, Assessment of Electric Vehicle and Battery Technology, April 2011. Available: https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/d2_en.pdf.

[34] Howell (2012), Battery Status and Cost Reduction Prospects, EV Everywhere Grand Challenge: Battery Workshop, Chicago, IL, July 26, 2012. Available: http://energy.gov/sites/prod/files/2014/03/f8/5_howell_b.pdf.

[35] Roland Berger (2012), Technology & Market Drivers for Stationary and Automotive Battery Systems, Nice, France, October 24-26, 2012. Available: http://www.rechargebatteries.org/wp-content/uploads/2013/04/Batteries-2012-Roland-Berger-Report1.pdf.

estimated current cost range in 2014, given as the mean of $410/kWh, and $300/kWh, respectively. This paper demonstrated that the annual global sale of light-duty BEVs increased more than 7 times from 2011 to 2014, and the cumulative battery capacity also increased from 600 MWh to 13,000 MWh during this period of time[36]. The authors believed that the 8 percent annual cost decline for market-leading actors is more likely to represent the probable future cost improvement for lithium-ion battery packs in BEV and revealed that the costs of lithium-ion battery packs continue to decline. The limitation of this study is that it does not specify battery chemistry or battery vocation application, though the data sources indicate that most of them are light-duty BEVs. Despite limited applications of this study, it demonstrates that substantial reduction in the cost of battery packs for light-duty BEVs is possible and that the reduction has occurred more rapidly than originally projected.

Figure 3: Cost of Lithium-ion Battery Packs in Light-Duty Battery Electric Vehicles



Source: Nykvist and Nisson, Nature Climate Change, 2015

4. Estimates from Electric Bus OEMs

Battery electric bus manufacturers have also provided information to the California Air Resources Board about current and projected battery costs or about projected bus costs.

[36] Nykvist, B. and Nilsson, M. (2015), Rapidly Falling Costs of Battery Packs for Electric Vehicles, Supplementary Sheet 2 (cumulative volume data), Nature Climate Change, doi: 10.1038/NCLIMATE2564.

Proterra's battery electric CATALYST Fast Charge™ transit bus operates with on-route fast charging technology and utilizes a 105 kWh LTO chemistry battery. Proterra estimates that the current LTO battery pack cost is upwards of $1000/kWh but did not provide a specific cost estimate. A midlife battery replacement of this battery, which is recommended after 6 years of heavy use (~40,000 miles per year), is projected to cost $75,000[29]. Proterra's battery electric CATALYST Extended Range™ transit bus uses an NMC battery with 330kWh of onboard energy storage[37]. According to Proterra, with the same 6 year midlife replacement schedule, the battery pack replacement is expected to yield significantly more onboard energy than today's offering while costing less than $200/kWh. Proterra also indicates there is a potential synergy with batteries for light-duty vehicles which utilize a tri-metal battery chemistry (such as NMC) that could reach a cell cost at or lower than $145/kWh – as was recently announced by GM for the upcoming Chevy Bolt battery[38].

BYD has indicated that the price of its 40-foot bus with a 324 kWh LFP battery is $770,000 in 2016 and is expected to decline year-over-year through 2025. Although BYD did not provide battery pricing, it does expect that battery pricing will fall by up to 33 percent in that same time period. To make a comparison to other battery cost estimates, we can approximate the battery costs by assuming the incremental cost of the BYD electric bus above a conventional diesel bus that costs $480,000 in 2016 is primarily from the battery cost. A rough estimate is $900/kWh in 2016 and around $600/kWh in 2025[39].

New Flyer indicates that the cost of lithium-ion battery systems for heavy-duty BEVs is expected to continue to have a premium compared to light-duty BEVs but may still benefit from lower battery cell costs with expansion of the light duty BEV market[28]. New Flyer's Xcelsior XE40 electric transit bus can be driven up to 130 miles per charge with a 300 kWh battery[40]. They state that the full-cost of battery systems for buses has previously been on the order of $750 to $850/kWh[28]. New Flyer explained that cost drivers for the premium over light duty vehicles include:

- Heavy-duty BEVs has lower purchasing volumes compared to light duty BEVs;

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[37] Proterra (2016), Proterra Announces Advancements in Battery Technology for Heavy Duty Transit, May 16, 2016. Available: http://www.proterra.com/proterra-announces-advancements-in-battery-technology-for-heavy-duty-transit/.

[38] James Ayre (2015), Chevy Bolt battery cells = $145/kWh, New Chevy Volt with autonomous driving, CleanTechnica, October 15, 2015. Available: http://cleantechnica.com/2015/10/05/chevy-bolt-battery-cells-145kwh-new-chevy-volt-with-autonomous-driving/.

[39] Reflects expected battery price reduction of 33% by 2025.

[40] New Flyer, New Flyer's Xcelsior Electric Bus Brochure. Available: https://www.newflyer.com/site-content/uploads/2018/03/Xcelsior-CHARGE-compressed.pdf.

- Battery thermal management systems (heating and cooling) are used in transit to ensure high performance and prevent thermal battery deterioration and shortened life;
- Battery rack packaging and securement structures are designed for a 12-year warrantable transit life;
- Individual power distribution units (PDUs) and battery management controllers (BCUs) are needed for each battery module added to achieve extended transit range.

Gillig also applied a 100kWh NMC battery to its first 30-foot battery electric bus from a third party supplier and expects to have a better estimate of their battery costs at scale when more buses are produced[29].

5. Summary of Costs

Figure 4 shows a plot of the battery cost estimates in nominal dollars per kWh from in Table 2 from various studies and indicates their applications and chemistries if available. "NS" is used if such information is not specified. Circles mean LTO batteries, squares mean LFP batteries, and diamonds mean NMC batteries. The median battery costs in 2015, 2020, and 2030 are calculated separately for LTO versus other battery technologies based on the data points in the figure. Note that the median of values for 2014, 2015, and 2016 is used to represent the median cost in 2015.

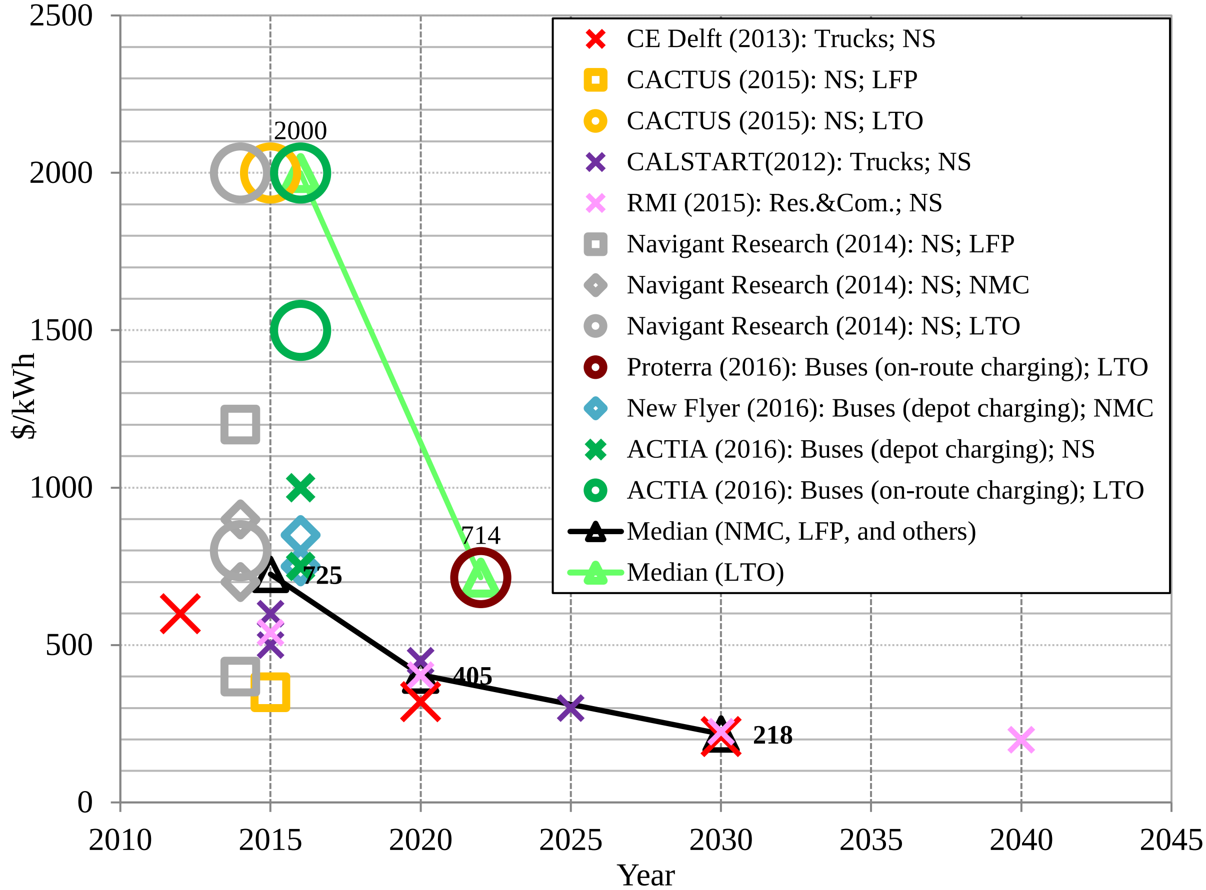
The battery costs for heavy-duty BEVs from these studies are currently in a very wide range of $350 to $2000/kWh, depending on battery chemistry. For 2015, LFP battery costs range from $350 to $1200/kWh, NMC battery costs are about $700 to $900/kWh and both are commonly used for depot charging.

For depot charging buses, we aggregate cost estimates for LFP and NMC together. The median battery costs from all estimates (excluding LTO) decline from $725/kWh in 2015 to $405/kWh in 2020 and to $218/kWh in 2030. By using these median values, a 324 kWh battery that is used in a bus that charges at a depot could have a price decrease of about $100,000 between 2016 and 2020 and is expected to decline further in price by 2030. The estimated battery price reduction from the aggregated data is also in-line with the bus price projection provided by BYD for their 40-foot depot charging bus where the bus price is expected to decline by about $100,000 ($770,000 in 2016 to an estimated $675,000 in 2025)[41]. Similarly, Proterra's extended range depot charging bus is expected to decline by about $130,000 in four years. Its

[41] Assumes a 33 percent battery price decline to $600/kWh*324 kWh=674,400.

incremental cost over a conventional CNG bus today is $234,000 and is expected to narrow to $104,000 over a conventional CNG bus in four years[42].

Figure 4: Battery Cost Estimates and Projections from Different Sources



Sources: CE Delft, 2013; CACTUS, 2015; CALSTART, 2012; RMI, 2015; Navigant Research, 2014; Proterra, 2016; New Flyer, 2016; ACTIA, 2016

LTO batteries are generally used for on-route charging buses with relatively small battery packs (compared to buses designed for depot charging) and their current costs range from $800 to $2000/kWh. There is only one LTO battery cost projection for 2022 from Proterra, based on its projected midlife replacement cost of $75,000 for its existing 105 kWh battery, as shown on the graph. Although there is insufficient data to develop a separate price trend for LTO batteries, Proterra confirms LTO battery prices are expected to continue to decline substantially. The battery cost reduction is reflected in

[42] This estimate is based on bus price projections from Proterra to the cost subgroup of Transit Agency Subcommittee, Steven Miller, Director of Maintenance at Golden Gate Bridge, Highway and Transportation District. The price declines are determined by comparing the incremental cost for a Proterra's buses to that of a CNG bus in a 4 year period.

the price of their on-route charging bus that is expected to decline about $130,000 in 4 years.

Batteries represent one of the most significant costs for battery electric buses. There is a clear expectation from the studies we evaluated that the trend in battery price reductions for heavy duty applications will continue for the foreseeable future. The median of the expected battery price reductions are consistent with bus price projections from Proterra and the battery cost reduction estimate from BYD. Lower battery costs per kWh are expected to result in significantly lower battery electric bus prices, longer range (for the same battery pack volume), or both depending on market factors. Although midlife battery replacements aren't expected for some buses, battery cost reductions are also expected to lower the cost for midlife battery replacements in about 6 to 8 years, when needed.

F. References

The following documents are the technical, theoretical, or empirical studies, reports, or similar documents relied upon in proposing these regulatory amendments, identified as required by Government Code, section 11346.2, subdivision (b)(3). Additionally, each appendix References the documents upon which it relies, as required by Government Code, section 11346.2, subdivision (b)(3).

Note: Each "Explanatory Footnote" is a footnote containing explanatory discussion rather than referencing specific documents relied upon.

1. National Research Council (2012), Review of the 21st Century Truck Partnership, Second Report. 2012. Available: http://nap.edu/13288.

2. California Air Resources Board (CARB) (2015), Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses, October 2015. Available: www.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf.

3. Element Energy (2012), Cost and Performance of EV Batteries: Final Report for the Committee on Climate Change, March 21, 2012. Available: www.element-energy.co.uk/wordpress/wp-content/uploads/2012/06/CCC-battery-cost_-Element-Energy-report_March2012_Finalbis.pdf.

4. Battery University (2016), Safety of Lithium-ion Batteries, Last Updated August 10, 2016. Available: http://batteryuniversity.com/learn/article/safety_of_lithium_ion_batteries.

5. Boston Consulting Group (BCG) (2010), Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020. Available: www.bcg.com/documents/file36615.pdf.

6. Navigant Research (2014), The Lithium Ion Battery Market: Supply and Demand. ARPA E RANGE Conference, January 28, 2014. Available: www.arpa-e.energy.gov/sites/default/files/documents/files/Jaffe_RANGE_Kickoff_2014.pdf.

7. BYD (2016), Personal Communication with Michael Austin, Vice President of BYD America, on March 9, 2016.

8. IDTechEx (2016), Electric Bus Sector is Game Changer for Battery Market, March 04, 2016. Available: http://www.idtechex.com/research/articles/electric-bus-sector-is-game-changer-for-battery-market-00009175.asp.

9. CACTUS (2015), Models and Methods for the Evaluation and Optimal Application of Battery Charging and Switching Technologies for Electric Busses. Available:

http://www.cactus-emobility.eu/CACTUS_Deliverable_1.2_Technologies-to-enable-fully-electric-busses.pdf.

10. NEI Corporation, Lithium Titanate Based Batteries for High Rate and High Cycle Life Applications. Available: http://neicorporation.com/white-papers/NEI_White_Paper_LTO.pdf.

11. Sakti, A. S., Michalek, J. J. , Fuchs, E. R. H., and Whitacre, J. F. (2015), A Techno-Economic Analysis and Optimization of Li-Ion Batteries for Light-Duty Passenger Vehicle Electrification, Journal of Power Sources, 273, 966–980. Available: https://doi.org/10.1016/j.jpowsour.2014.09.078.

12. Electric Power Research Institute (EPRI) (2010), Large-Format Lithium-ion Battery Costs Analysis: Critical Review of Existing PHEV Lithium Ion Battery Cost Studies, December 2010. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001019923.

13. Nelson, P. A., Santini, D. J., and Barnes, J. (2009), Factors determining costs of lithium-ion batteries for PHEVs, EVS24, Savanger, Norway, May 13-16, 2009. Available: http://www.cars21.com/web/assets/link/EVS-24-3550250%20santini.pdf.

14. Miller, J. F. (2010), Analysis of current and projected battery manufacturing costs of electric, hybrid, and plug-in hybrid electric vehicle, EVS25, Shenzhen, China, November 5-9, 2010. Available: http://www.evs24.org/wevajournal/php/download.php?f=vol4/WEVA4-4050.pdf.

15. Edison Electric Institute (EEI) (2014), Transportation Electrification: Utility Fleets Leading the Charge, June 2014. Available: http://www.eei.org/issuesandpolicy/electrictransportation/fleetvehicles/documents/eei_utilityfleetsleadingthecharge.pdf.

16. Argonne National Laboratory (2012), Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Second Edition, ANL-12/55, December 2012. Available: http://www.cse.anl.gov/batpac/files/BatPaC%20ANL-12_55.pdf.

17. Argonne National Laboratory (2016), Email Communication with Paul Nelson and Shabbir Ahmed, Chemical Engineers, on May 5, 2016.

18. Tan, G., Wu, F., Zhan, C., Wang, J., Mu, D., Lu, J., and Amine, K.(2016), Solid-State Li-Ion Batteries Using Fast, Stable, Glassy Nanocomposite Electrolytes for Good Safety and Long Cycle-Life, Nano Letter, 16 (3), 1960–1968, DOI: 10.1021/acs.nanolett.5b05234.

19. Wang, Y., Richards, W.D., Ong, S.P., Miara, L.J., Kim, J.C., Mo, Y., and Ceder, G. (2015), Design Principles for Solid-State Lithium Superionic Conductors, Nature Materials, 14, 1026–1031. Available: https://doi.org/10.1038/nmat4369.

20. MIT News (2015), Going Solid-State Could Make Batteries Safer and Longer-Lasting, August 17, 2015. Available: http://news.mit.edu/2015/solid-state-rechargeable-batteries-safer-longer-lasting-0817.

21. Hassan, F.M., Batmaz, R., Li, J., Wang, X., Xiao, X., Yu, A., and Chen, Z. (2015), Evidence of Covalent Synergy in Silicon-Sulfur-Graphene Yielding Highly Efficient and Long-Life Lithium-Ion Batteries, Nature Communications, doi:10.1038/ncomms9597.

22. Christian Ruoff (2015), Tesla Tweaks Its Battery Chemistry: A Closer Look at Silicon Anode Development, September 23, 2015. Available: https://chargedevs.com/features/tesla-tweaks-its-battery-chemistry-a-closer-look-at-silicon-anode-development/.

23. National Research Council (NRC) (2013), Transitions to Alternative Vehicles and Fuels. Available: http://nap.edu/18264.

24. Venkat Srinivasan (2015), The Future of (Electrochemical) Energy Storage, Lawrence Berkeley National Lab, April 22, 2015. Available: https://www.arb.ca.gov/research/seminars/srinivasan/srinivasan.pdf.

25. CE Delft (2013), Zero Emissions Trucks: An Overview of State-of-the-Art Technologies and Their Potential, July 2013. Available: http://www.theicct.org/sites/default/files/publications/CE_Delft_4841_Zero_emissions_trucks_Def.pdf.

26. CALSTART (2012), Best Fleet Uses, Key Challenges and the Early Business Case For E-Trucks: Findings and Recommendations of the E-Truck Task Force. 2012. Available: http://www.calstart.org/Libraries/E-Truck_Task_Force_Documents/Best_Fleet_Uses_Key_Challenges_and_the_Early_Business_Case_for_E-Trucks_Findings_and_Recommendations_of_the_E-Truck_Task_Force.sflb.ashx.

27. Rocky Mountain Institute (2015), The Economics of Load Defection: How Grid-Connected Solar-Plus-Battery Systems Will Compete with Traditional Electric Service, Why It Matters, and Possible Paths Forward, April 2015. Available: https://rmi.org/insight/economics-load-defection/.

28. New Flyer (2016), Email Communication with David Warren, Director of Sustainable Transportation, on June 13, 2016.

29. Proterra (2016), Email Communication with Dustin Grace, Director of Battery Engineering, on June 9, 2016.

30. Transit Agency Subcommittee (2016), Email and Personal Communications with Cost Subgroup, Steven Miller, Director of Maintenance at Golden Gate Bridge, Highway and Transportation District.

31. Nykvist, B. and Nilsson, M. (2015), Rapidly Falling Costs of Battery Packs for Electric Vehicles, Nature Climate Change, doi: 10.1038/NCLIMATE2564.

32. Fuel Cells and Hydrogen (FCH) (2012), Urban Buses: Alternative Powertrains for Europe, A Fact-Based Analysis of the Role of Diesel Hybrid, Hydrogen Fuel Cell, Trolley and Battery Electric Powertrains, June 12, 2012. Available: https://www.fch.europa.eu/node/790.

33. ICF (2011), Impacts of Electric Vehicles – Deliverable 2, Assessment of Electric Vehicle and Battery Technology, April 2011. Available: https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/d2_en.pdf.

34. Howell (2012), Battery Status and Cost Reduction Prospects, EV Everywhere Grand Challenge: Battery Workshop, Chicago, IL, July 26, 2012. Available: http://energy.gov/sites/prod/files/2014/03/f8/5_howell_b.pdf.

35. Roland Berger (2012), Technology & Market Drivers for Stationary and Automotive Battery Systems, Nice, France, October 24-26, 2012. Available: http://www.rechargebatteries.org/wp-content/uploads/2013/04/Batteries-2012-Roland-Berger-Report1.pdf.

36. Nykvist, B. and Nilsson, M.(2015), Rapidly Falling Costs of Battery Packs for Electric Vehicles, Supplementary Sheet 2 (cumulative volume data), Nature Climate Change, doi: 10.1038/NCLIMATE2564.

37. Proterra (2016), Proterra Announces Advancements in Battery Technology for Heavy Duty Transit, May 16, 2016. Available: http://www.proterra.com/proterra-announces-advancements-in-battery-technology-for-heavy-duty-transit/.

38. James Ayre (2015), Chevy Bolt battery cells = $145/kWh, new Chevy Volt with autonomous driving, CleanTechnica, October 15, 2015. Available: http://cleantechnica.com/2015/10/05/chevy-bolt-battery-cells-145kwh-new-chevy-volt-with-autonomous-driving/.

39. Explanatory Footnote

40. New Flyer, New Flyer's Xcelsior Electric Bus Brochure. Available: https://www.newflyer.com/site-content/uploads/2018/03/Xcelsior-CHARGE-compressed.pdf.

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