Charging the Future

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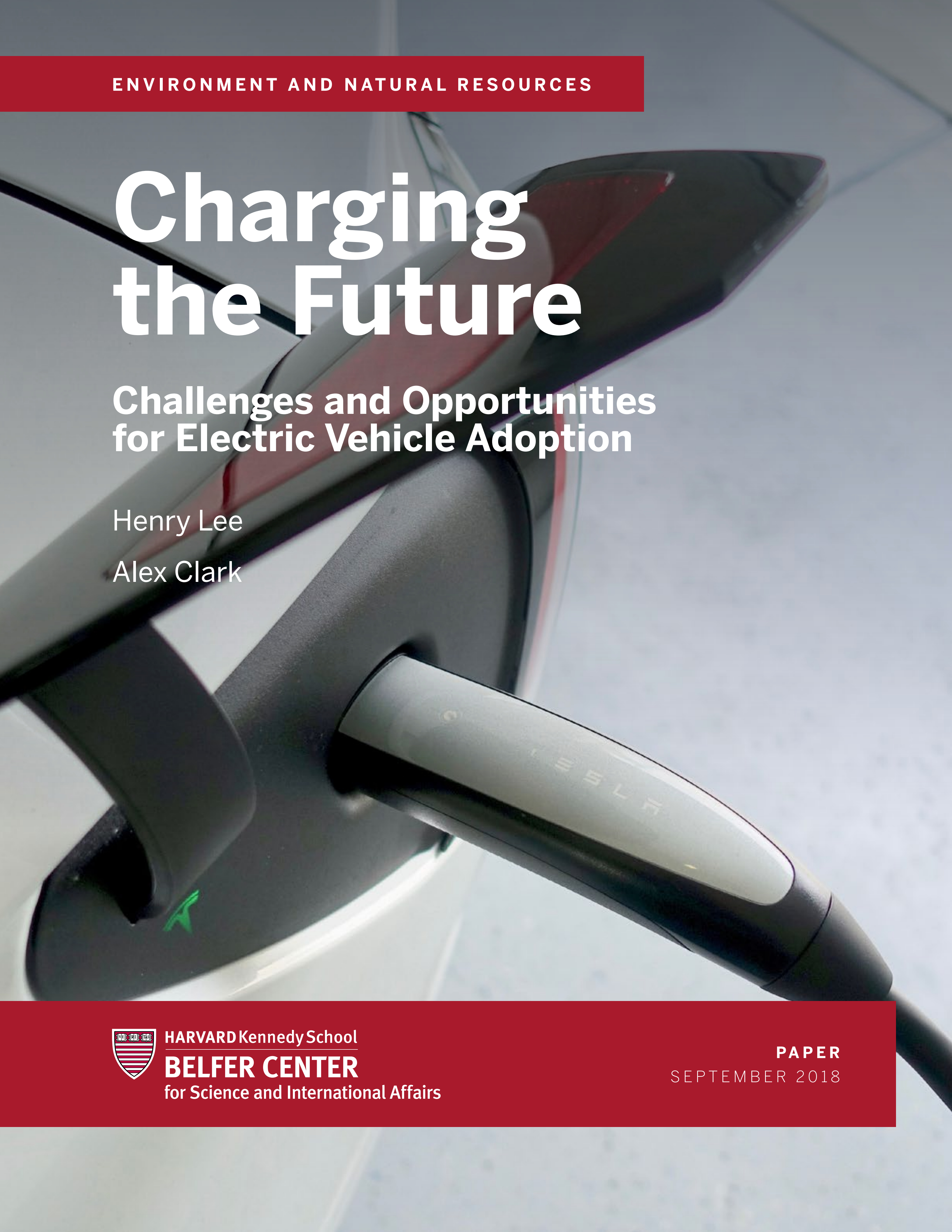

Charging the Future

Challenges and Opportunities for Electric Vehicle Adoption

Henry Lee

Alex Clark

HARVARD Kennedy School
BELFER CENTER
for Science and International Affairs

PAPER
SEPTEMBER 2018

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Cover photo: A Tesla Model 3 charges using a Mobile Charger 2.0, 29 July 2017.
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About the Project

The Environment and Natural Resources Program at the Belfer Center for Science and International Affairs is at the center of the Harvard Kennedy School's research and outreach on public policy that affects global environment quality and natural resource management. Its mandate is to conduct policy-relevant research at the regional, national, international, and global level, and through its outreach initiatives to make its products available to decision-makers, scholars, and interested citizens.

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Cover Image
A Tesla Model 3 charges using a Mobile Charger 2.0, 29 July 2017.

Executive Summary

Electric vehicles (EVs) have advanced significantly this decade, owing in part to decreasing battery costs. Yet EVs remain more costly than gasoline fueled vehicles over their useful life. This paper analyzes the additional advances that will be needed, if electric vehicles are to significantly penetrate the passenger vehicle fleet.

Battery Prices

Cell costs have plummeted to $145 per kWh or lower, and are expected to continue falling with technological improvements and returns to large-scale production. While cells are only one component of the cost of an installed battery, the cost of installed batteries has declined from around $1,000 per kWh in 2010 to an estimated $250-350 per kWh in 2018. Total battery costs are falling more slowly, as consumers demand EVs with longer ranges and thus larger batteries. Meanwhile, governments are finding it increasingly difficult to fiscally justify large subsidies to attract buyers.

Will Declining Battery Costs Make EVs Competitive?

This paper compares the lifetime costs of battery-only cars (BEVs), plug-in hybrids (PHEV) and gasoline-fueled internal combustion-engined vehicles (ICE), using a range of gasoline prices, discount rates, and battery costs. The PHEV is more expensive than the ICE in almost all scenarios, while the BEV is robustly cost-competitive, once installed battery prices reach $200-$250 per kWh. Hence, further reductions in battery costs will still be needed for BEVs to be a viable alternative to ICEs.

The paper compares the lifetime costs of the Chevrolet Bolt BEV to the costs of an equivalent PHEV and ICE, using a range of gasoline prices, discount rates, and battery costs. The PHEV is more expensive than the ICE in almost all scenarios, while the BEV is cost-competitive once battery prices reach $200-$250 per kWh.

Will Charging Infrastructure Support EV Adoption?

Commercial success for EVs will require installing charging infrastructure that is accessible, easy to use, and relatively inexpensive—whether at home or in public locations. The form this infrastructure will take is still uncertain, with a range of charging technologies currently available and more expected to emerge over the next five years. The current range of equipment spans slower alternating current (AC) chargers best suited to home or office locations and short trips (Level 1-2 in this paper), and much faster direct current fast chargers (DCFC) for rapid refueling in public locations, best suited for recharging on longer journeys (Level 3-5). The time taken to add 100 miles of range varies from 26 hours for the slowest AC charger, to six minutes for the fastest DCFC charger—still far slower than the 300 miles-per-minute enjoyed by a 30 mile-per-gallon ICE.

The costs of charging infrastructure are both fixed (installation, utility service, transformers, and equipment) and variable (electricity charges). For chargers on commercial electricity tariffs, demand charges can dominate operating costs. As a result, the total cost of power from fast charging stations is higher than slower residential chargers unless the former can achieve sufficiently high utilization rates.

Modeling different types of charging infrastructure and comparing them with the operating costs of an ICE suggests that simple home charging is competitive with today's more efficient gasoline cars and could be significantly cheaper if a time-of-use electricity tariff, with lower prices in off-peak periods, is in place. More powerful home charging is sensitive to capital costs, but is competitive with moderately efficient ICEs and substantially cheaper under a time-of-use tariff. For commercial chargers (Level 3-5), the price of electricity required for investment in the system to break even falls sharply at progressively higher utilization rates. At 30% utilization, all variants are cheaper than fueling an average ICE, and at 40% utilization, they are competitive with an efficient ICE.

At current levels of utilization (optimistically, 10%), commercial chargers are almost universally not economically profitable, suggesting a significant, sustained increase in demand will be needed for commercial charging infrastructure to deliver financial returns, and compete with both ICEs and cheaper residential charging.

Managing additional power demand from EVs is both a challenge and an opportunity for distribution utilities. High concentration of EV home charging during peak periods can overload local transformers. Utilities may have to procure additional peak capacity, unless they are able to shift demand to off-peak periods. Time-of-use electricity pricing, along with smart metering, have already been deployed in some states to incentivize off-peak charging and manage peak loads, respectively. It is unclear whether they will be sufficient to offset demand increases. Vehicle-to-grid technology, allowing EVs to serve as mobile electricity storage units, could complement these efforts but will need adequate incentives, which are not presently available. Overall, electricity tariff reforms will be essential, if today's power systems will be able to serve the additional demand from the significant deployment of electric vehicles.

Introduction

Over the past decade there has been a growing interest, bordering on enthusiasm, for electric vehicles. Is the American motorist on the cusp of replacing gasoline-powered cars with electric versions? Will gasoline stations be superseded by fast charging stations? Will the transportation sector of the future be electrified? These questions are at the core of the energy and transport debates. Governments have enacted subsidy programs, supported the installation of a charging infrastructure, and are starting to develop regulatory initiatives to support and manage an electric vehicle fleet. In fact, some governments—including the United Kingdom and France—have announced that they will not permit the sale of new fossil-fueled automobiles after 2040.[1] The car manufacturers that were initially skeptical about electric vehicles are now committing billions of dollars to their production. By 2022 there will be 127 different fully battery-electric car models available for purchase in the United States.[2]

Is this euphoria justified by the state of the technology and by economic and financial realities? Six years ago, a Harvard paper attempted to address this question.[3] Its conclusion was that under most business-as-usual scenarios, efficient fossil-fueled automobiles would continue to have a cost advantage over electric vehicles. At the time, the future of electric vehicles depended largely on a combination of high government subsidies, extremely high gasoline prices (over $4.50 per gallon), and dramatic improvements in battery technology. Today, the outlook is more positive, but several of the same unresolved questions remain. Will battery powered electric vehicles be competitive with conventional gasoline-fueled vehicles in the next five to ten years? Will a cost-effective charging infrastructure emerge? What are the economic and financial challenges that must be overcome?

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[1] Ryan, C. and J. Shankleman. 26 July 2017. "U.K. Joins France, Says Goodbye to Fossil-Fuel Cars by 2040". Bloomberg. https://www.bloomberg.com/news/articles/2017-07-25/u-k-to-ban-diesel-and-petrol-cars-from-2040-daily-telegraph

[2] Naughton, K. 19 December 2017. "The Near Future of Electric Cars: Many Models, Few Buyers". Bloomberg. https://www.bloomberg.com/news/features/2017-12-19/the-near-future-of-electric-cars-many-models-few-buyers

[3] See Lee, H. and G. Lovellette. 2011. "Will Electric Cars Transform the U.S. Market?" Harvard Kennedy School Faculty Research Working Paper Series RWP11-032. https://research.hks.harvard.edu/publications/getFile.aspx?Id=715

First, over the past six years, battery costs have fallen significantly, but the size of battery packs has increased. In other words, in the course of addressing range anxiety, the total cost of an EV battery pack has declined more slowly than the cost per kilowatt-hour (kWh). As a result, installed battery costs continue to be a barrier to widespread consumer acceptance. This paper reviews the status of these costs and the levels that must be reached if electric cars are to become cost-effective alternatives.

Second, while battery costs have attracted the interest and the pocket books of both car manufacturers and the electronics industry (Samsung, LG, Panasonic etc.), the challenges around designing and operating a financially viable charging infrastructure to serve EV batteries remain. There are different types of home-charging equipment, and multiple commercial-charging station configurations, with no clear winner in the current market. Who will develop a commercially profitable plan to charge the electric cars of the future—the electric utility companies? The automobile manufacturers? The equipment manufacturers? Or third-party investors? None of these candidates has yet to implement a sustainable long-term business plan. The good news is that manufactures, utilities and other parties are moving quickly to develop inter and intra-city charging options, but significant regulatory and financial complexities may retard widespread economically sustainable deployment. This paper examines these complexities, and how they affect the cost of fueling and operating an electric vehicle.

1. Battery Technology

Improvements in battery technology over the past six years have been impressive. Today's battery cells have higher energy densities and are much less expensive on a per kWh basis than they were just a few years ago. Lithium-ion (Li-ion) cells enjoy the bulk of investment, and remain the preferred technology for LG Chem, Panasonic, and Samsung, the three largest producers. Lithium-metal technologies with much higher energy densities are in development, but currently lack the production scale and established supply chain advantages of Li-ion.[4]

Verifiable information on battery costs is difficult to obtain, owing to both intense commercial sensitivity and confusion over the definition of "battery"—which can apply to the cost of individual cells, the battery pack, or the battery pack once installed in the vehicle itself, or indeed the final cost to the consumer once any manufacturer markup is applied. These distinctions are explained below, and unless otherwise stated, "battery costs" in subsequent sections of this paper refer to the total cost to the consumer.

The sharp downward trend in the cost of Li-ion cells, however, is clear. From a baseline of about $1,000 per kWh for an installed battery. Cell manufacturing costs have declined about 70% since 2010 due primarily to economies of scale.[5] This holds across different configurations and chemical compositions, and is the largest contributor to observed cost declines, with an average of 8% cost reduction for a doubling in volume every year since 2010.[6] Compounded from 2010-2015, this equates to a 35% real decline in cost due to economies of scale, accounting for almost half of the total cost reductions seen since 2010. Nykvist and Nilsson's (2015) study concurs with this finding, attributing 30% of cost reductions from 2013-2017 to economies of scale, and the remainder to declines in material

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[4] Samsung, among others, has been developing graphene-based battery technologies. Despite recent research advances, the technology is still focused on mobile device applications. It remains some distance from commercialization in any form, and further away from deployment at the scale required for a car battery. Jung-a, S. 27 November 2017. "Samsung hails "graphene ball" battery success". Financial Times. https://www.ft.com/content/5a6693f0-d349-11e7-8c9a-d9c0a5c8d5c9

[5] Boston Consulting Group. 2010. "Batteries for Electric Cars: Challenges, Opportunities and the Outlook to 2020." Boston, MA: Boston Consulting Group.

[6] Faguy, P. 2015. "Overview of the DoE Advanced Battery R&D Program". U.S. Department of Energy. https://energy.gov/sites/prod/files/2015/06/f23/es000_faguy_2015_o.pdf

costs and learning rates, with an estimated combined annual cost decline (including both learning rate and returns to scale) of 12-14%.[7]

As noted already, cell costs are only a part of the total installed cost of the battery. Using available information on battery sales to manufacturers, McKinsey's 2017 *Electrifying Insights* report implies an underlying Li-ion cell cost of approximately $150 per kWh at the end of 2016, and an additional cost of roughly $70-100 per kWh to convert cells into battery packs. McKinsey's figures correspond with the more optimistic end of projections from earlier studies, citing an installed battery pack cost (to the car manufacturer) of $227 per kWh in 2016.[8] This is roughly in line with U.S. Department of Energy trend estimates that put battery pack costs for 14 kWh plug-in hybrid EVs (PHEVs) at $289 per kWh in 2015, with potential for economies of scale alone to push this down further to $200 per kWh.[9] By McKinsey's estimate, battery pack costs are projected to fall to $190 per kWh by 2020.[10] The McKinsey report implies that these decreases will come primarily as a result of further technological advances in the production of the cells themselves, rather than reductions in capital costs stemming from scaled-up efficiency, but the report does not explain where specifically these advances will be made.

The International Energy Agency's 2018 *Global Electric Vehicle Outlook* estimates cell costs at $145 per kWh, and gives its range of estimates for installed battery pack costs at $155-$360 per kWh, depending heavily on production scale and battery size. Their mid-range estimate of the total cost to the consumer is $274 per kWh, based on comparing pricing of models with ICE and BEV powertrains.[11] This in turn implies the difference between cell cost and total cost to the consumer is in the vicinity of $130 per kWh. Given the inherent uncertainties in these estimates, we assume this difference is between $100-$200 per kWh, implying a total cost to the consumer of $245-$345 per kWh (see Table 1.1). This additional cost reflects an additional manufacturer mark-up over the cost of materials

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[7] Nykvist, B. and M. Nilsson. 2015. "Rapidly falling costs of battery packs for electric vehicles". Nature Climate Change 5: 329-332. doi:10.1038/nclimate2564.

[8] McKinsey & Company. 2017. "Electrifying Insights - How auto makers can drive electrified vehicle sales and profitability." New York, NY: McKinsey & Company.

[9] Faguy, P. 2015. "Overview of the DoE Advanced Battery R&D Program."

[10] McKinsey & Company. 2017. "Electrifying Insights."

[11] International Energy Agency. *Global EV Outlook 2018: Towards cross-modal electrification.* p.66.

and assembly to recover capital investment and research and development, and to achieve a rate of return. In the latter case, there may be substantial variation across manufacturers, depending on whether their electric vehicle sales are intended to be profit-making. Assuming that the existing price ranges reflect some form of manufacturer discount to boost demand, we contend that financially sustainable pricing is currently in the $300-$400 per kWh range.[12]

Table 1.1 Battery cost estimates across stages of production

Stage of Production	Estimated Cost per kWh
Cell cost Purchasing Lithium-ion cells from the cell manufacturer	$145
Pack assembly Arranging cells into a battery pack	$215-245 (combined cost implied from difference between cell cost and installed cost, using McKinsey $70-$100 estimate)
Pack covering and preparation Wrapping battery in protective materials ready for installation	
Installed pack Installation into the vehicle. Includes wiring, circuitry and inverters	
Total cost to consumer Price markup between capital cost to manufacturer and price charged to consumer. Covers additional labor and capital costs to OEM.	$245-345 (total cost implied from difference between cell cost and total cost to consumer, using a $100-$200 estimate implied from IEA $274 mid-range figure)

Battery pack prices are generally difficult to ascertain with any precision and the ultimate cost to the consumer depends on supply chain dynamics, manufacturer mark-up, and scale. In Table 1.1, we break down estimates of the various components of battery costs. While the figures for cell cost, installed cost, and final cost (including markup) are roughly consistent, the largest information gap is in the stages between purchasing cells and installing the battery pack into an EV drivetrain (including pack assembly, covering it with protective material, wiring, circuitry, safety measures, and an AC/DC inverter). Allowing for a wide margin of error, it is reasonable

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[12] As noted below, the Chevrolet Bolt is an example of a loss-making vehicle. It is often unclear in these cases whether discounted pricing is applied to the batteries or the vehicle as a whole, and whether it is part of a strategy to stimulate demand, or to avoid penalties for non-compliance with clean vehicle regulations.

to conclude that the total cost of an EV battery by the end of 2017 was in the region of $250-$350 per kWh, and likely to fall as competitive pressure builds, technology improves, and large-scale production continues to produce returns to scale.

1.1 Challenges to Wider Deployment

The declining per-kWh cost of batteries is happening at the same time that battery pack sizes are increasing. In search of increased range, manufacturers are augmenting the size of battery packs on new models. The base-model Nissan Leaf powertrain grew from 24 kWh to 30 kWh for the first generation, then to 40 kWh for the second generation (announced in September 2017),[13] while Tesla's Model S base model has grown from offering 60 kWh, to 70 kWh, with a 100 kWh model released in August 2016.[14] The delicate balance between using larger batteries to improve performance and range, and keeping costs affordable, is not lost on an industry in which "unfavorable battery economics will remain a profitability barrier for the next two to three product cycles".[15]

Nonetheless, OEMs are investing heavily in building up EV production capacity. In addition to offering a PHEV version of every model it makes, Volkswagen Group expects to offer 30 battery-only electric vehicles (BEVs) by 2025, making up 25% of all new sales,[16] while Ford plans 13 BEV models by 2022. The Chinese government has a target of 8% of all sales being BEVs or PHEVs in 2018, and a coalition of eight U.S. states, including California, is aiming for a total of 3.3 million EVs on their roads by 2025.[17] In Norway, BEVs and PHEVs accounted for a third of new sales in 2016, with a target of 400,000 BEVs by 2020. Norway's success is at least

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[13] Nissan USA. 2017. "Build your 2018 Nissan Leaf." https://www.nissanusa.com/electric-cars/2018-leaf/configure/

[14] Lambert, F. 2016. "Tesla's new Model S P100D is not only quick, it's the first all-electric car with over 300 miles of range." Electrek. https://electrek.co/2016/08/24/tesla-model-s-p100d-first-all-electric-car-over-300-miles-range/

[15] McKinsey & Company. 2017. "Electrifying Insights."

[16] Campbell, P. 26 July 2016. "Electric cars see range, battery and ease of charging as barriers to mass adoption." Financial Times. https://www.ft.com/content/8f79ae6e-2400-11e6-9d4d-c11776a5124d

[17] The Economist. 18 February 2017. "Volts wagons: Electric cars are set to arrive far more speedily than anticipated."

partly due to exceptionally low hydroelectric power costs for charging, and effective policy measures offering a host of additional benefits to EV drivers (including free parking and charging) and exemptions from purchase taxes that typically double the cost of a gasoline powered vehicle.[18]

Meeting this expected EV demand will require an unprecedented build-up of battery procurement capacity and capital investment, with the transition likely to be loss-making in the short term as established OEMs shift capital and labor resources rapidly towards EV mass-production. U.S. bank Morgan Stanley projects Volkswagen's entire automobile business may be loss-making from 2025-2028 as a consequence.[19] Affordable supplies of critical materials for battery manufacturing, notably cobalt, may be placed under pressure, while assembly plants will require large capital investments to scale up EV production sufficiently.[20]

1.2 **Subsidies**

The U.S. federal credit instituted by the Obama Administration of up to $7,500 per car, depending on the capacity of the battery, is valid for up to 200,000 PHEVs or BEVs sold and registered with the Department of Transport by each independent manufacturer, regardless of model. From the 200,000th vehicle onwards, the program is phased out so as not to disrupt the market or confuse consumers. The full $7,500 credit continues through to the end of the financial quarter in which the 200,000th vehicle is produced, and through the following quarter. The maximum credit falls to $3,750 for the following six months, and $1,875 for the next six months after that, before expiring completely. Between selling the 200,000th vehicle and the credit's expiration, the manufacturer can build and sell an

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[18] The Economist. 18 February 2017. "Northern light: Sales of green vehicles are booming in Norway." http://www.economist.com/news/business/21717063-ever-more-electric-cars-are-road-next-step-build-charging-network-support

[19] The Economist. 18 February 2017. "Volts wagons: Electric cars are set to arrive far more speedily than anticipated."

[20] Lithium market dynamics are certainly an area for further exploration in terms of geopolitics, trade and economic scarcity, but not expanded upon here because lithium typically only comprises 1-3% of battery costs, so even in the event of large demand spikes, is unlikely to affect battery prices very much.

unlimited number of EVs, receiving the applicable incentive for all cars produced within the authorized period.[21]

Additional subsidies are available in some states. California's existing program is three times higher than most other states, but most EVs are not eligible for the full amount, typically enjoying a maximum rebate of $2,500. Unfortunately for California EV buyers, the allocated funds were exhausted as of June 30, 2017, at which point only low-income applicants remained eligible.[22] The California Air Resources Board is scheduled to release a study in early 2019 on the appropriate size of any future subsidy. Elsewhere, governments have found subsidies for electric vehicles to be fiscally unsustainable. China, Denmark, Norway, and France, amongst others, are in the process of replacing direct financial subsidies with increased regulatory programs, such as exemptions from highway tolls or excise fees.[23]

While subsidies may provide benefits in terms of learning, a sustainable transition to electric vehicles will not be driven by generous government subsidies, but rather by fundamental economics and technology improvement.

1.3 **Lifetime Costs**

The fully-electric Chevrolet Bolt, with an approximate 238-mile range and list price of $37,495, is priced at $27,500 once the $7,500 federal subsidy and an average $2,500 state subsidy are accounted for. The list price of the Tesla Model 3 (with a range of 200 miles), starting at $33,000, is reduced to $23,000 once subsidies are accounted for, but this discount will not continue much longer, as Tesla's eligibility for the full federal subsidy starts to expire.

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[21] Internal Revenue Service. 2017. "Plug-In Electric Drive Vehicle Credit (IRC 30D)." https://www.irs.gov/businesses/plug-in-electric-vehicle-credit-irc-30-and-irc-30d

[22] California Clean Vehicle Rebate Project. 2017. "Vehicles and Eligibility." https://cleanvehiclerebate.org/eng

[23] Hertzke, P., Müller, N. and S. Schenk. July 2017. "Dynamics in the global electric vehicle market." McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/dynamics-in-the-global-electric-vehicle-market

We constructed a simple financial model to compare the net present cost, over a ten-year lifetime, of a Chevrolet Volt (PHEV), Chevrolet Bolt (BEV) and a comparable ICE, the Chevrolet Impala.[24] The results are summarized in Table 1.2. To provide some indication of the true comparability of EVs with ICEs, federal or state subsidies are *not* included in our calculations of the total cost of ownership. The Swiss bank UBS estimates that General Motors will lose $7,400 on the sale of each Bolt, implying it would have to price the car at $44,895 to break even.[25] Other sources quote the loss to be as high as $9,000 per vehicle, implying a breakeven price of $46,495.[26] However, for each Bolt sold in California (its largest market), GM receives four Zero-Emission Vehicle (ZEV) credits valued at about $4,000 each, meaning it can still ultimately make a profit on each sale. In the absence of independent verification of the loss estimates, we assume these loss estimates are exaggerated and that the actual loss is half of the maximum quoted figure (i.e. $4,500)—implying a breakeven price of $41,995. We compare the ICE's total cost of ownership at list price ($27,095) to the Volt at list price ($33,220), and the Bolt, at its list price ($37,495), and its suggested breakeven price ($41,995), to understand what it might take for the Bolt to be profitable.

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[24] The Impala is chosen as it is likely more representative of mass-market models being produced by major European and American manufacturers in the next 5-10 years than the more luxurious, upmarket models favored by Tesla.

[25] UBS. 18 May 2017. "Q-Series: UBS Evidence Lab Teardown—Disruption Ahead?" http://www.advantagelithium.com/_resources/pdf/UBS-Article.pdf.

[26] Welch, D. and J. Lippert. 2016. "GM's Ready to Lose $9,000 a Pop and Chase the Electric Car Boom." Bloomberg. https://www.bloomberg.com/news/articles/2016-11-30/gm-s-ready-to-lose-9-000-a-pop-and-chase-the-electric-car-boom.

Table 1.2 Net present cost comparison of representative BEV (Chevrolet Bolt) and PHEV (Chevrolet Volt) models, without subsidies and assuming cars are charged at home on residential rates. ICE (Chevrolet Impala) is basis for cost comparison.

Gas = gas price per gallon, r = discount rate.

Battery: $400/kWh	**Additional cost (savings) vs. ICE**		
	PHEV (list price)	BEV (list price)	BEV (breakeven price)
Gas $2.10, r = 10%	$5,680	$6,029	$10,529
Gas $2.50, r = 10%	$4,643	$4,755	$9,255
Gas $3.00, r = 10%	$3,346	$3,163	$7,663
Gas $2.10, r = 15%	$5,762	$6,830	$11,330
Gas $2.50, r = 15%	$4,915	$5,789	$10,289
Gas $3.00, r = 15%	$3,855	$4,489	$8,989
Gas $2.10, r = 20%	$5,822	$7,418	$11,918
Gas $2.50, r = 20%	$5,114	$6,548	$11,048
Gas $3.00, r = 20%	$4,229	$5,462	$9,962

Battery: $300/kWh	**Additional cost (savings) vs. ICE**		
	PHEV (list price)	BEV (list price)	BEV (breakeven price)
Gas $2.10, r = 10%	$3,880	$29	$4,529
Gas $2.50, r = 10%	$2,843	($1,245)	$3,255
Gas $3.00, r = 10%	$1,546	($2,837)	$1,663
Gas $2.10, r = 15%	$3,962	$830	$5,330
Gas $2.50, r = 15%	$3,115	($211)	$4,289
Gas $3.00, r = 15%	$2,055	($1,511)	$2,989
Gas $2.10, r = 20%	$4,022	$1,418	$5,918
Gas $2.50, r = 20%	$3,314	$548	$5,048
Gas $3.00, r = 20%	$2,429	($538)	$3,962

Battery: $200/kWh	**Additional cost (savings) vs. ICE**		
	PHEV (list price)	BEV (list price)	BEV (breakeven price)
Gas $2.10, r = 10%	$2,080	($5,971)	($1,471)
Gas $2.50, r = 10%	$1,043	($7,245)	($2,745)
Gas $3.00, r = 10%	($254)	($8,837)	($4,337)
Gas $2.10, r = 15%	$2,162	($5,170)	($670)
Gas $2.50, r = 15%	$1,315	($6,211)	($1,711)
Gas $3.00, r = 15%	$255	($7,511)	($3,011)
Gas $2.10, r = 20%	$2,222	($4,582)	($82)
Gas $2.50, r = 20%	$1,514	($5,452)	($952)
Gas $3.00, r = 20%	$629	($6,538)	($2,038)

The analysis accounts for fuel costs and maintenance costs, calculated and discounted annually. Maintenance costs are highest for the two-engined PHEV, and lowest for the BEV which has a comparatively simple electric motor. Assuming a $400 per kWh final battery cost as the base case (the higher end of our estimates), we varied final battery costs, gasoline prices, and discount rates to assess their effect on EV competitiveness.[27] We assume all EV charging takes place at home and is billed at $0.1759 per kWh, the average 2016 domestic electricity rate in California (the U.S.' largest EV market).[28] Average annual mileage is derived from the 2016 U.S. figure of 13,476 miles per year, or 36.9 miles per day.[29] The combined average energy consumption of a BEV on the market today, according to the United States EPA, ranges from 0.27 kWh per mile for the Volkswagen e-Golf and BMW i3, to 0.32 kWh per mile for the Tesla Model S.[30] Unless otherwise stated, this analysis assumes a higher figure of 0.37 kWh per

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[27] Recent research has identified an implied discount rate for individual vehicle purchases of 15%. See Allcott, H. and N. Wozny. 2014. "Gasoline Prices, Fuel Economy, and the Energy Paradox." The Review of Economics and Statistics. Vol. 96, No.5. 779-795. doi:10.1162/REST_a_00419

[28] U.S. Energy Information Administration. 2017. "Electricity data browser." https://www.eia.gov/electricity/data/browser/.

[29] Federal Highway Administration. 2016. "Average Annual Miles per Driver by Age Group." U.S. Department of Transportation. https://www.fhwa.dot.gov/ohim/onh00/bar8.htm

[30] U.S. Department of Energy. 2017. "2018 Best and Worst Fuel Economy Vehicles." http://www.fueleconomy.gov/feg/best-worst.shtml

mile to accommodate systematic downward bias in official fuel economy estimates[31] and more aggressive driving styles. We vary the gasoline prices to cover a range from the low and high prices of the last three years, and we use three discount rates 10%, 15% and 20% (designated by "r" in Table 1.2). Most economists and most OEMs use the higher discount estimates, since American car buyers tend to hold their cars for less than the useful life of the vehicle. See Appendix A1 for a full list of assumptions.

The figures in Table 1.2 suggest that at battery prices greater than $300 per kWh, hybrid vehicles (PHEVs) are more costly than ICEs, and only cheaper at $200 per kWh under high gas prices and low discount rates. At the (ICE) Chevrolet Impala's 26 miles per gallon (mpg), gasoline fuel costs range from $0.08 per mile ($2.10 per gallon) to $0.11 per mile ($3.00 per gallon), while the (PHEV) Volt averages 42 miles-per-gallon equivalent, or $0.05-$0.07 per mile, for the 70% of the time it is assumed to run as a gasoline-electric hybrid, for the remaining 30% of the time, running on electricity alone, it costs $0.1759 per kWh, or $0.065 per mile.

BEVs are more competitive. The Chevrolet Bolt, on 100% battery power and assuming residential charging rates, costs $0.065 per mile to run—significantly cheaper to fuel than the ICE. If the installed battery costs are reduced below $200, the BEV will be less expensive than the ICE and will be close to cost competitive at battery prices below $250 per kWh. It is important to remember that these cost figures are for installed batteries and are without subsidies. The BEV price is more sensitive to lower battery prices than the PHEV. It also incurs lower maintenance costs than a PHEV having just one motor rather than two, with few moving parts. Unsurprisingly, then, at a battery cost of $200 per kWh, the BEV's net present cost is $4,600-$8,800 cheaper than the ICE, and even more so when compared to the PHEV.

However, there is strong evidence to suggest that the electric vehicle manufacturer's list price is set significantly below actual costs. Once the assumed $4,500 loss is accounted for (i.e. applying the breakeven price), the BEV has a $7,700-$11,900 higher net present cost than the ICE at $400 per kWh. At

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[31] Tanaka, S. 2018 forthcoming. "Mind the Gap! Tax Incentives and Incentives for Manipulating Fuel Efficiency in the Automobile Industry."

$200 per kWh, the BEV is cheaper in every scenario by between $80 and $4,300. This suggests that while selling BEVs at a loss may make sense to gain market share, experience in the BEV market, further reductions in final battery costs, or lower electricity prices, will still be needed for BEVs to be a viable long-term alternative to an ICE. Further, as ICEs and PHEVs are becoming incrementally more fuel-efficient, the competitive pressures on BEVs are not likely to abate.

Our analysis would benefit from more reliable cost data to gauge with precision which factors will be important in driving down the present cost of installed batteries and thus BEVs. Consumer research indicates that potential EV buyers price in other factors into their purchase decision (including persistent, if not necessarily warranted, concerns over vehicle safety and range anxiety).[32] PHEVs, while appearing less competitive than BEVs in the figures above, may have practical advantages over BEVs not reflected in our cost analysis.

On the other hand, trends in battery costs and the prices of EVs are declining. If these trends continue, electric vehicles could be cost competitive with gasoline power cars over their lifetime early in the next decade. This does not mean that ICEs are in danger of losing their markets, since it will take time for consumers to become comfortable with electric vehicles and, as we discuss in the next few sections, the absence of a charging infrastructure remains a major barrier.

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[32] McKinsey & Company. 2017. "Electrifying Insights."

2. Charging Infrastructure

Without an accessible infrastructure that can re-charge an EV in a reasonable period of time, most motorists will be unwilling to purchase one, even if it is cheaper and its performance is better. Admittedly, the risk of being stranded without power is small, but it is one that today's motorists have not faced in the vehicles that they have driven throughout their lifetimes.

The commercial success of the electric vehicle will require the development of a charging infrastructure that is accessible, easy to use, and relatively inexpensive. While there are many charging technologies available and more in the pipeline, there is no consensus on what an effective infrastructure will look like thirty years from now. In fact, there is less certainty in 2018 than there was six years ago, when BEV batteries were smaller, and relatively inexpensive to charge. Plugging a 24 kWh Nissan Leaf into a normal "Level 1" 1.4 kW residential outlet in the evening and unplugging it the next morning would recharge half the battery, require no additional capital outlay, and the electricity would cost approximately $60 per month, assuming the vehicle was charged every day. Impatient or heavy users could install a "Level 2" 220-volt (6.6 kW) system for $1,500-$2,200 and fully recharge their Leaf in seven hours.[33]

These options become less attractive when the BEV has a 70-100 kWh battery, which will be more common as the BEV industry attempts to overcome consumer range anxiety. It would take fifty hours to fully charge a 70 kWh Tesla Model S from a normal wall outlet, and almost eleven hours with a 220-volt, 6.6 kW line. Tesla has developed a home charging system that can triple the electric output of a 220 volt line,[34] bringing recharging time down to under four hours, but total installed costs of the charging equipment can reach $4,000-$6,000 depending on the buyer's specific requirements.[35] If these newer BEVs are being driven long distances between charges, home charging technology will have to improve

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[33] See Lee, H. and G. Lovellette. 2011. "Will Electric Cars Transform the U.S. Market?"

[34] See detailed footnote in "Level 1 and 2: Alternating Current," under section 2.1 below.

[35] Tesla has been willing to assume all or part of this cost depending on individual circumstances, but whether it will continue to do so in the future, and to what degree, is uncertain and the financial sustainability of such a policy depends on cross-selling of other Tesla products, such as home battery storage systems.

dramatically or commercial fast-charging stations will have to be widely deployed if electric vehicles are to compete with gasoline-fueled cars.

Owners of a conventional vehicle are unlikely to switch to an electric car, if the fueling process is more difficult, time consuming, and uncertain. Commercial fast-charging stations are beginning to emerge in locations across the United States, Europe, and Asia, but, in Tesla's case at least, they are intended to facilitate the sale of the vehicle, as opposed to being a commercial standalone operation. If these facilities are to be deployed at scale, they will need to be accessible to all electric car models, and will require viable business plans—plans that will provide an opportunity for investors to make a positive return on their investments. All of this is possible, but the uncertainties around technologies, regulations, and costs will have to be substantially reduced.

The following section addresses several questions: What are the charging options that are, and may become, available? What are their costs? How does the speed of charging infrastructure affect its commercial viability?

To answer these questions, we present a simple financial model to quantify the underlying economic factors affecting charging. Our focus is on the capital costs of building and installing charging equipment, the variable costs of supplying it with electrical power, and the revenue required for charging infrastructure to break even, including a discussion of the opportunity cost of time spent waiting for EVs to charge. We conclude by briefly addressing the economic challenges around load management in scenarios with high EV penetration, and suggesting avenues for further research.

2.1 The Charging Challenge

Energy efficiency, distributed energy resources, and shifting demand patterns have been a challenge to American electric utilities for some time. Since 2010, annual electricity demand has been flat or declining in many regions. In the Southwest alone, annual electricity demand in 2016 was 2.7

million MWh less than forecasted.[36] Rapid EV deployment will increase the demand for power, but the existing generating capacity should be able to meet that demand in most areas of the country, assuming that a percentage of that incremental demand occurs in the off-peak hours. Utilities are less concerned about the eventual magnitude of this incremental demand, than the form that EV charging might take—how fast, where and when, and how the power will be priced. These parameters will be critical determinants in the evolution of the EV charging market.

2.1.1 **Types of EV Charging Equipment**

Charging equipment, henceforth denoted by "electric vehicle supply equipment" (EVSE) comes in two basic varieties. The first, comprising "Level 1" and "Level 2" EVSE, operates using alternating current (AC), and can draw electricity directly from the local distribution system. [37] All BEVs and PHEVs carry an on-board inverter with limited capacity, to convert AC power to direct current (DC), which is required to charge the battery. The second variety, "Level 3" and above, uses DC charging, which bypasses the need for an inverter by charging the battery directly and can therefore deliver much more power. There is otherwise no relevant difference in the AC and DC charging process. Chargers in public or commercial locations, typically Level 2 and above, (henceforth "commercial chargers") may be standalone devices, or stations comprised of multiple chargers.

Level 1 and Level 2: Alternating Current

Level 1, providing 1.4 kW of power in the United States, is simply a conventional wall socket, and requires no additional circuitry, aside from the adapters required to connect the EV to the socket. In theory, Level 1

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[36] Salisbury, M. and W. Toor. 2016. "How Leading Utilities are Embracing Electric Vehicles." Boulder, CO: Southwest Energy Efficiency Project. http://www.swenergy.org/data/sites/1/media/documents/publications/documents/How_Leading_Utilities_Are_Embracing_EVs_Feb-2016.pdf

[37] In the U.S., the standard frequency of AC power (the amount of times per second the current reverses itself) is 60 Hertz, at a potential of approximately 110 volts. In most other parts of the world, including Europe, the corresponding values are 50 Hertz and 220 volts, providing twice the power. This is only relevant for Level 1 (wall-plug) charging, which can take place twice as fast on a 220V system.

charging can be used anywhere, although in practice it takes place primarily at the EV owners' homes.

Level 2 charging operates on the same upgraded 220-volt outlets, required by washing machines and clothes driers, and can easily be installed. More modern houses typically have these outlets, while older houses may require electrical upgrades. Depending on the home's electrical infrastructure, this can involve upgraded circuitry, wiring extensions to reach the charging location, or, even in rare cases, an upgraded transformer. Level 2 charging can also be provided at workplace locations, other business locations (hotels, gas stations, private parking lots), and public locations (on-street parking space, garages, streets, public parking lots—wherever cars are likely to be stationary for hours at a time). Level 2 charging starts at a power rating of 6.6 kW, increasing to 19.2 kW depending on the level of current that the supporting circuitry can sustain. Most home Level 2 charging, and almost all commercial Level 2 charging, is limited to 6.6 kW because (a) the onboard inverter on most existing EVs cannot handle significantly more than this level[38] and (b) boosting the current typically requires the installation of more expensive higher-capacity circuitry.[39]

Level 3 and above: Direct Current

Because direct current charging bypasses an EV's onboard inverter to charge the battery directly, it can deliver much higher levels of electrical power. This type of charger is commonly referred to as a Direct Current Fast Charger (DCFC) and is typically used only in commercial locations. While studies demonstrate that consistently high DCFC usage can accelerate deterioration in battery capacity over time, capacity degradation for

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[38] Additional inverter capacity can be installed, but it will increase the cost of the vehicle.

[39] Tesla EVs are one of the few exceptions. The Tesla High-Powered Wall Connector (HPWC), a product sold separately from its cars, can boost Level 2 charging up to 16.8 kW depending on the available circuitry and inverter capacity (out of a theoretical Level 2 maximum of 19.2 kW). Being able to use the HPWC is one of the benefits of driving a Tesla Model S or X, which come with one 10kW onboard inverter as standard, with an additional 10kW inverter as optional. Being able to take advantage of the full potential of the HPWC usually requires some form of circuit upgrade from the standard 20-30 amperes, to 60-100+ amperes. Most publicly-subsidized Level 2 EVSE are limited to 6.6 kW because of federal grant conditions linked to the cost of power and equipment (higher amperage increases the capital and operating costs of charging). Further, for public Level 2 EVSE subject to commercial rate schedules and therefore demand charges, it can be in the operator's interest to limit peak power.

the vast majority of users is more closely associated to overall usage than charging patterns.[40] "Estimated Direct Current Fast Charger utilization rates," an NREL study concludes, "do not appear frequent enough to significantly impact battery life," suggesting that the thermal management systems of the battery itself are a more important determinant.[41] Self-reported survey data from Tesla drivers suggests that even for the most frequent users of fast charging, battery capacity is highly unlikely to fall below 90% of its original rating even after 150,000 miles of usage.[42]

For the purposes of this paper, DCFC charging is classified as follows:

- Level 3 charging is used to refer to a power delivery of **50 kW**;
- Level 4 corresponds to **150kW**;
- Level 5 (ultra-fast DCFC) corresponds to **350kW**.

Most third-party DCFC chargers are Level 3, operating at about 50kW. Tesla's proprietary network of Superchargers, with a typical power output of 120 kW, is designed to serve Tesla vehicles exclusively and corresponds most closely to Level 4. Level 5 ultra-fast DCFC, which requires heavy-duty insulation equipment, has not yet been deployed on a commercial basis, and no mass-produced EVs can currently handle this level of power. EVSE operator ChargePoint announced a 400kW charging platform in January 2017[43] and a consortium of OEMs (Porsche, Ford, Daimler and

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[40] Shirk, M. and J. Wishart. 2015. "Effects of Electric Vehicle Fast Charging on Battery Life and Vehicle Performance. Presented at SAE 2015 World Congress and Exhibition, Detroit, Michigan. 21-23 April 2015. https://avt.inl.gov/sites/default/files/pdf/vehiclebatteries/FastChargeEffects.pdf

[41] Neubauer, J., E. Wood, E. Burton, K. Smith and A.A. Pesaran. "Impact of Fast Charging on Life of EV Batteries." National Renewable Energy laboratory. Presented at EVS28, KINTEX, Korea. 3-6 May 2015. https://www.nrel.gov/docs/fy15osti/63700.pdf

[42] Teslarati. 2017. "Tesla battery degradation analysis reveals how long a battery might last." http://www.teslarati.com/how-long-will-tesla-battery-last-degradation/ Tesla Model X and S variants include an eight-year or 100,000-120,000 mile warranty for the battery itself, while the more recent Model 3 includes a guarantee for 70% of battery capacity over the full eight-year warranty period. See Lambert, F. 2017. "Tesla releases Model 3 warranty with new 70% battery capacity retention guarantee". Electrek. https://electrek.co/2017/12/20/tesla-model-3-warranty-new-battery-capacity-retention-guarantee/

[43] ChargePoint. 5 January 2017. "ChargePoint Enables the Future of Mobility with Express Plus Electric Vehicle Charging Platform." https://www.chargepoint.com/about/news/chargepoint-enables-future-mobility-express-plus-electric-vehicle-charging-platform/

Volkswagen Group) is involved in a joint venture aiming to install a 350kW network across Europe.[44]

Table 2.1 presents each charger type, its nominal power rating (in kW), the time taken to replenish the expected average daily usage of 13.65 kWh described above, the time taken to replenish 100 miles of charge (i.e. 37 kWh, just under half of a 75 kWh battery), and the miles of range added per minute of charging. Charging time is assumed to depend entirely on the power rating of the charger, although in practice, technical limitations on the battery, electrical supply, and inverter capacity (for AC charging) can add time to the process. It is assumed that the rate of charging is linear (i.e. does not slow down significantly over the course of the session).[45] This is a reasonable simplifying assumption, since the rate of charging does not diminish significantly until the battery reaches approximately 90% of capacity,[46] and most public charging sessions are used to partially recharge batteries rather than fully recharge them. Users of EVGo's Level 3 network in California, for instance, average just 5-12 kWh per session (or enough to drive an additional 15-36 miles).[47] The reference battery size of 75 kWh reflects a reasonable expectation of average battery size of BEVs over the next five years—larger than the current Chevrolet Bolt (60kW) and smaller than the top-end Tesla Models S and X (90-100 kWh).

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[44] BMW Group. 29 November 2016. "BMW Group, Daimler AG, Ford Motor Company and Volkswagen Group with Audi & Porsche Plan a Joint Venture for Ultra-Fast, High-Power Charging Along Major Highways in Europe". *BMW Group*. https://www.press.bmwgroup.com/global/article/detail/T0266311EN/bmw-group-daimler-ag-ford-motor-company-and-volkswagen-group-with-audi-porsche-plan-a-joint-venture-for-ultra-fast-high-power-charging-along-major-highways-in-europe?language=en

[45] Li-ion batteries, also used in cell phones, do not actually charge in a linear fashion; the rate of charge declines as the battery approaches full capacity. This means that an EV putting a full charge on an empty battery charges the first 80% more quickly than the remaining 20%. The rate of decline varies according to the specific EV model. Since the typical user does not usually charge a battery from completely depleted to completely full, this non-linearity should not have a significant impact on average charging speeds.

[46] Van der Put, R. 2016. "How fast charging works." https://fastned.nl/en/blog/post/how-fast-charging-works

[47] See Fitzgerald, G. and C. Nelder. 2017. "EVGo Fleet and Tariff Analysis. Phase 1: California." Boulder, CO: Rocky Mountain Institute. https://www.rmi.org/wp-content/uploads/2017/04/eLab_EVgo_Fleet_and_Tariff_Analysis_2017.pdf. EVGo's data also reveals significant differences in average charge sessions across commercial locations. Charging in retail locations draws an average of 5.7 kWh (about 15 miles) per session and customers arrive with batteries that are already 30-50% charged, suggesting they are using the stations to "top off" the battery. Charging in car dealerships deliver 11.5 kWh (31 miles) per session, and motorists tend to arrive with less charge on their battery, suggesting a more premeditated usage pattern or longer average stay, or a combination of both—but still topping up, rather than fully recharging. The averages for gas stations and hotels are 9.3 kWh and 10.2 kWh respectively: somewhere in-between. As newer cars have ever larger battery packs, these numbers are likely to rise.

Table 2.1 Variants and charging characteristics of EV chargers, assuming power usage of 0.37 kWh per mile.

Charger Type	Current Type	Average Power Delivered (kW)	Time taken to replenish daily usage (13.65 kW)	Time taken to charge 100 miles (37 kWh)	Range added per minute (miles)
Level 1	AC	1.4	9h 45m	26h 26m	0.06
Level 2 [standard]	AC	6.6	2h 4m	5h 36m	0.30
Level 2 [maximum]	AC	19.2	43m	1h 55m	0.86
Level 3	DC	50.0	16m	44m	2.25
Level 4	DC	150.0	5m	15m	6.76
Level 5	DC	350.0	2m	6m	15.77

As Table 2.1 demonstrates, even ultra-fast Level 5 charging still takes six minutes to half-fill a 75 kWh battery, and would take twelve minutes or more to fully recharge from empty. As batteries become larger, moving towards 100-150 kW, these charging times will lengthen. Even with Level 5 charging, producing 15.8 miles of additional range per minute, the time it takes to repower an EV, is not comparable to conventional gasoline refueling. Reducing refueling time to the 300 miles per minute enjoyed by a 30 mpg ICE refueling at 10 gallons per minute[48] would require a charger 19 times more powerful, or 6.7 MW. This is far beyond the scope of what is possible today and likely to remain so for the foreseeable future. Under almost every scenario, charging an electric vehicle will take more time than fueling an ICE.

Refueling a gasoline car is so quick and easy, that almost any other option is less convenient. Journeys over 300 miles will require at least one charging stop. Adding just 100 miles of range with a Level 4 charger—the fastest charging option currently in service—would take at least fifteen minutes. Refueling completely (about 300 miles) would take about 45 minutes. Further, the flow of vehicles through gasoline stations is much greater, owing to the rapidity of

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[48] Electronic Code of Federal Regulations. 2017. “Title 40 §80.22—Controls and prohibitions.” https://www.ecfr.gov/cgi-bin/text-idx?SID=68da1c87ec7a2f6cb7934cf89740d0e6&mc=true&node=se40.19.80_122&rgn=div8

refueling. In areas with charging station congestion or stations where customers typically leave their car to charge while they do something else (shopping, for example), there may be an additional delay waiting for a space to open up, extending the wait for a 100 mile recharge to 30 minutes or more.

2.2 **Understanding Charging Economics**

2.2.1 **Fixed Costs**

EV users will pay for two costs: the equipment to recharge the vehicle (fixed costs) and the power that is consumed (variable or energy costs). The fixed costs associated with different types of electric vehicle supply equipment (EVSE) have three main components: (1) the cost of installing the equipment and where relevant the cost of site preparation; (2) utility system upgrades, such as new transformers; and (3) the cost of the charging equipment. The first two can be jointly described as "make-ready" infrastructure, which includes everything except the charging equipment itself. Table 2.2 below summarizes estimates of the different fixed cost categories for each level of charging.

The first component is the cost of *installation and site preparation* (which includes electrical service extension, permitting, labor costs, and trenching to lay cables). These costs are generally non-existent for Level 1, and minimal for residential Level 2 unless the installation of new circuitry is required. Installation costs are substantially higher for commercial or public Level 2 chargers, which usually consist of a physical "tower," akin to a gasoline dispenser or a street parking ticket machine.[49] Commercial Level 2 EVSE usually require some form of wiring extensions, the installation of signage and trenching to install the additional connections to the grid. Installation costs are highly location-specific, since each EVSE has unique requirements. Thus, the range of cost estimates is very wide. A comprehensive Idaho National Laboratory review finds installation costs ranging from $600-$12,700 for Level 2 (across residential

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[49] This is not always the case—Level 2 EVSE in hotels and parking lots, for instance, may be simpler.

and commercial),[50] and $4,000-$51,000 for DCFC commercial installations.[51] Further, the labor costs vary significantly and contribute, on average, 55-60% of the installation cost.[52]

Table 2.2 Fixed cost estimates for each type of EV charger

Capital Costs	Residential		Commercial			
	Level 1	Level 2	Level 2	Level 3	Level 4	Level 5
Installation (per charger)[A]	$0	$1,354	$3,108	$22,626	$22,626	$22,626
Site preparation (per charger)	0	0	3,000[B]	12,500[C]	12,500	12,500
Utility service (per station)	0	0	4,000	17,500[D]	17,500	17,500
Transformer (per station)	0	0	5,698[E]	32,500[F]	40,000[G]	40,000
Equipment (per charger)	0	1,000[H]	3,842[I]	35,000[J]	50,000	100,000

A Idaho National Laboratory. 2015c. "Plugged In: How Americans Charge Their Electric Vehicles. Findings from the largest plug-in electric vehicle infrastructure demonstration in the world." https://avt.inl.gov/sites/default/files/pdf/arra/PluggedInSummaryReport.pdf

B Logios Consulting. 2013. "Lessons From Early Deployments of EV Charging Stations: Case Studies from the Northeast and Mid-Atlantic Regions." Prepared for the Transportation and Climate Initiative. https://www.nyserda.ny.gov/-/media/Files/Programs/ChargeNY/Lessons-Early-Deployments-of-EVSE.pdf

C, D Clint, J., et al. 2015. "Considerations for Corridor Direct Current Fast Charging Infrastructure in California."

E ChargePoint. 25 November 2015. "Northern California Express Corridor Project Corridor 1." Submission in response to California Energy Commission GFO-15-601: DC Fast Chargers for California's North-South Corridors.

F, G Clint, J., et al. 2015. "Considerations for Corridor Direct Current Fast Charging Infrastructure in California."

H M.J. Bradley & Associates. 2013. "Electric Vehicle Grid Integration in the U.S., Europe, and China: Challenges and Choices for Electricity and Transportation Policy." Prepared for Regulatory Assistance Project and International Council on Clean Transportation. http://www.theicct.org/sites/default/files/publications/EVpolicies_final_July11.pdf

I Smith, M. and J. Castellano. 2015. "Costs Associated with Non-Residential Electric Vehicle Supply Equipment."

J Clint, J., et al. 2015. "Considerations for Corridor Direct Current Fast Charging Infrastructure in California."

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[50] Idaho National Laboratory. 2015a. "How do Publicly Accessible Charging Infrastructure Costs Vary by Geographic Location?" The EV Project, INL/MIS-15-35319. http://avt.inl.gov/pdf/EVProj/HowDoPubliclyAccessibleInfrastructureInstallationCostsVaryByGeographicLocation.pdf

[51] Idaho National Laboratory. 2015b. "What is the Impact of Utility Demand Charges on a DCFC Host?" INL/EXT-15-35706. http://avt.inl.gov/pdf/EVProj/EffectOfDemandChargesOnDCFCHosts.pdf

[52] Smith, M. and J. Castellano. 2015. "Costs Associated with Non-Residential Electric Vehicle Supply Equipment: Factors to consider in the implementation of electric vehicle charging stations." New West Technologies. Prepared for the U.S. Department of Energy Vehicle Technologies Office.

The second major cost (in which a number of chargers are typically connected to the same local network and transformer), is the *utility infrastructure upgrade* required to provide the EVSE with power. In some circumstances, these upgrades will be minimal or unnecessary; in others, they will be a major component of the overall costs. Where more than one charger is located in the same place, the infrastructure requirements may be correspondingly greater, since the peak demand will be larger. A single Level 2 EVSE is unlikely to require a transformer upgrade, but several operating simultaneously on the same circuit (for instance, several EV owners in the same neighborhood, charging at the same time) may place the existing transformer at risk of overload, and require an upgrade.

As EV penetration increases, some utilities will face the need to invest in upgrading their distribution infrastructure. The rate of investment will be influenced by the design of the tariff schedule and the commercial penetration of smart-charging systems to optimize the temporal demand on the system.

Costs will be much higher for Level 3-5 fast charging installations. For example, these facilities typically require a new transformer at a cost of $30,000-$40,000, although increasing the number of chargers per station can reduce the per-charger cost of a transformer to $10,000-$25,000, and the per-charger cost of service extensions to $3,500-$9,500.[53]

The third cost is that of the *equipment* itself (i.e. the EVSE). Once again, these costs will vary across charger types, and several estimates are available for each type. A typical Level 1 home charger requires no additional equipment. Level 2 home EVSE can cost up to $1,000, while commercial Level 2 EVSE “towers” can cost $3,000-$4,000 for a charger with an electronic interface, payment system, and network connection.[54] DCFC (Level 3-5) EVSE is significantly more expensive, typically costing about $30,000-$40,000 for a single-port charger and $50,000-$60,000 for a dual-port charger. These cost estimates will vary across manufacturers and specifications.

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[53] Smith, M. and J. Castellano. 2015. “Costs Associated with Non-Residential Electric Vehicle Supply Equipment.”

[54] Mims, C. 28 August 2016. “Why EVs will be here sooner than you think.”

Alternative Energy Systems places the total cost of a four-DCFC system at $205,000 budgeting approximately $30,000 apiece for each DCFC, $20,000 for installation, $17,500 for utility service extensions, and $40,000 for a 500 kVA transformer.[55] Other estimates suggest that the installation and equipment costs could be even higher.[56]

Returns to scale on capital costs are, therefore, possible for larger DCFCs organized into multi-charger stations, but these returns would be dependent on the ability of the station to maintain sufficiently high utilization rates (i.e. the percentage of time that the EVSE is actually dispensing electricity) to ensure that revenues recover the outlay for each additional charger.[57] By means of comparison, the average utilization rate of gasoline stations in the United States—many with multiple pumps—is approximately 34%, while those of commercial EVSE are typically closer to 5-10%.[58] A ten percent utilization rate for an asset costing $160,000 is not a financially viable proposition, as the modeling below will illustrate. The charging events required to maintain a high level of utilization will increase proportionally with the number of chargers in any given station. Any time in which a car has completed charging, but remains idly plugged in to the charging cable, is using up space without generating revenue. Thus, achieving even a modest 20% utilization target on a daily basis may prove challenging, even in areas with high EV penetration.

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[55] Clint, J., et al. 2015. "Considerations for Corridor Direct Current Fast Charging Infrastructure in California."

[56] Total costs for a single DCFC can easily total $150,000 or more. California utility Pacific Gas & Electric (PG&E) proposes building 50 standalone DCFCs at a total present cost of $248,000 apiece (although this includes a financial rate of return that it is legally required to provide for). See Pacific Gas & Electric. 2017b. "PG&E & Clean Energy Programs." Presentation, April 7th, 2017.

[57] Clint, J., B. Gamboa, B. Henzie, and A. Karasawa. 2015. "Considerations for Corridor Direct Current Fast Charging Infrastructure in California." Alternative Energy Systems Consulting. Prepared for California Energy Commission. CEC-600-2015-015. http://www.energy.ca.gov/2015publications/CEC-600-2015-015/CEC-600-2015-015.pdf

[58] Keeney, T. 2016. "Update—Supercharger: A Charge Could Cost Half the Price of Gas." ARK Invest. https://ark-invest.com/research/supercharger-cost-comparison#fn-6240-12

2.2.2 **Variable Energy Costs**

Residential Charging

In most cases, the electricity drawn by Level 1 and Level 2 chargers at home would be charged at a fixed, residential rate per kWh consumed, although some utilities already offer EV-specific time-of-use (ToU) rates designed to encourage owners to charge at night or during off-peak periods. These rates offer low prices at off-peak times (usually at night) and significantly higher prices during peak times (mid-afternoon and early evening). Users can choose to charge in the afternoon at a premium rate, or overnight at a discounted rate. ToU rates can have multiple price brackets depending on the utility and service area, with mid-range prices for partial peaks, and higher peak prices in the summer than the winter.

Each BEV can be expected to increase a household's electricity demand (hence also its electricity bill) by between 25-40%.[59] A University of Central Florida analysis estimates that on a levelized basis, charging a car at home will cost a BEV owner $0.18 per kWh on average. This is in line with the average California 2016 residential electricity rate of approximately $0.1759 per kWh,[60] and accounts for the modeled impact of ToU pricing, in which a percent of charging is shifted to lower-priced off-peak hours. At a fixed residential electricity rate of $0.1759 per kWh and 13.65 kWh daily usage, corresponding roughly to 36.9 miles a day—the average distance a U.S. motorist drives—the cost of electricity for residential users would be $72.04 per month, or $0.065 per mile traveled. The average fuel efficiency of light-duty short wheel base U.S. vehicles in 2015 was 24 mpg, [61] which at a relatively low gasoline price of $2.50 per gallon, would cost $0.104 per mile traveled. A comparatively efficient ICE achieving 40 mpg (more representative of the competition EVs will face) would cost $0.063 per mile traveled, roughly the same as an EV charged at residential rates. This implies that the average electricity cost for an EV should be equal to,

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[59] Salisbury, M. and W. Toor. 2016. "How Leading Utilities are Embracing Electric Vehicles."

[60] See U.S. Energy Information Administration. 2017. "Electricity data browser."

[61] U.S. Department of Transportation. 2016. "Table 4-23: Average Fuel Efficiency of U.S. Light Duty Vehicles." Bureau of Transportation Statistics. https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_23.html

or lower than, the $~0.17 per kWh benchmark to compete with an efficient ICE. Table 2.3 compares these costs. The first column lists the price in cost per mile and the second, the equivalent cost per kWh.

Table 2.3 Illustrative fuel costs for BEV vs ICE for residential charging without ToU rates applied, at 0.37 kWh per mile and $2.50 per gallon of fuel.

Vehicle	Fuel cost ($/mile)	Implied equivalent cost per BEV kWh ($)
BEV	0.065	0.176
ICE (24 mpg)	0.104	0.282
ICE (40 mpg)	0.063	0.169

Commercial Charging

Electricity used by commercial chargers is usually metered using commercial and industrial electricity rates, which in the majority of cases incorporate a per-peak-kW demand charge plus a volumetric per-kWh energy tariff. Commercial tariffs typically offer lower volumetric charges (an average of approximately $0.145 per kWh in 2016 compared to $0.1759 for residential[62]), but also employ demand charges of approximately $10-$17 per peak kW (set by the highest level of demand over any 15-minute period over the course of one month). Demand charges reflect the projected cost to the utility of providing the generation and distribution infrastructure required to meet peak demand on both a system level and a local distributional level. It is not a penalty charge, but rather a method

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[62] U.S. Energy Information Administration. 2017. "Electricity data browser."

by which the utility can recover its fixed costs of serving that customer.[63] These are the same utility upgrade costs described in the previous section.

Since the charge is incurred based on maximum, not average, load, it favors heavy, consistent loads and penalizes the short bursts of high power that DCFCs usually demand. Flexibility on demand and energy charges is of greater consequence the more powerful the charger, since the full demand charge is set by a single instance of high usage, regardless of the average level of utilization. Demand charges can be higher during the summer, and may also be layered into non-coincident charges (reflecting maximum demand at any time) for recovering local distribution system costs; and additional coincident charges (applied during peak times) for recovering infrastructure and generation costs incurred in meeting system peaks.

The average demand charge for commercial customers in the United States is $8.62 per kW of peak demand.[64] In California, investor-owned utility Southern California Edison (SCE) sets an EV-specific demand charge of $13.20 per kW,[65] while Pacific Gas and Electric (PG&E) sets a winter peak demand charge of $10.47 and summer charge of $17.84.[66] An independent study estimates the average demand charge faced by EVSE operators at $13 per kW.[67] Using this latter figure (applied throughout the rest of the paper), a *single* Level 3 50 kW charger at a commercial station would incur a demand charge of $650 per month, a Level 4 150kW charger, $1,950 per

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[63] The assumption of direct causation between an individual consumer's peak demand per month, and system capacity, is a controversial one; but less so for distribution capacity. Critics argue that since (a) demand charges typically have no time-of-use component and (b) individual peak demand does not necessarily correspond to system peak demand, there is not necessarily any correspondence between individual peak demand and the cost of distribution or generation. As noted, some utilities employ non-coincident versus coincident demand charges to differentiate between system peaks and individual peaks, but typically the non-coincident charge is higher (because it is unpredictable and falls outside the system peak for which the utility has contracted for, meaning it may have to purchase additional power on the spot market at higher prices or invest in additional local distribution infrastructure). This results in a perverse incentive for heavy users to keep their individual peak demand within the system peak demand, exacerbating the overall peak. Regulators in certain states, such as California, are exploring alternatives to demand charge that more accurately reflect the cost of individual peaks to system costs.

[64] Kettles, D. and R. Raustad. 2017. "Electric Vehicle Charging Technologies Analysis and Standards." Electric Vehicle Transportation Center, University of Central Florida. http://fsec.ucf.edu/en/publications/pdf/FSEC-CR-2057-17.pdf

[65] Southern California Edison. 2015. "Electric Car Rate Options—Rate Option 2: TOU-EV-4." https://www.sce.com/wps/portal/home/business/rates/electric-car-business-rates

[66] Pacific Gas & Electric. 2017b. "PG&E & Clean Energy Programs."

[67] Clint, J., et al. 2015. "Considerations for Corridor Direct Current Fast Charging Infrastructure in California."

month, and an ultra-fast Level 5 350 kW charger, $4,550 per month (see Table 2.4).

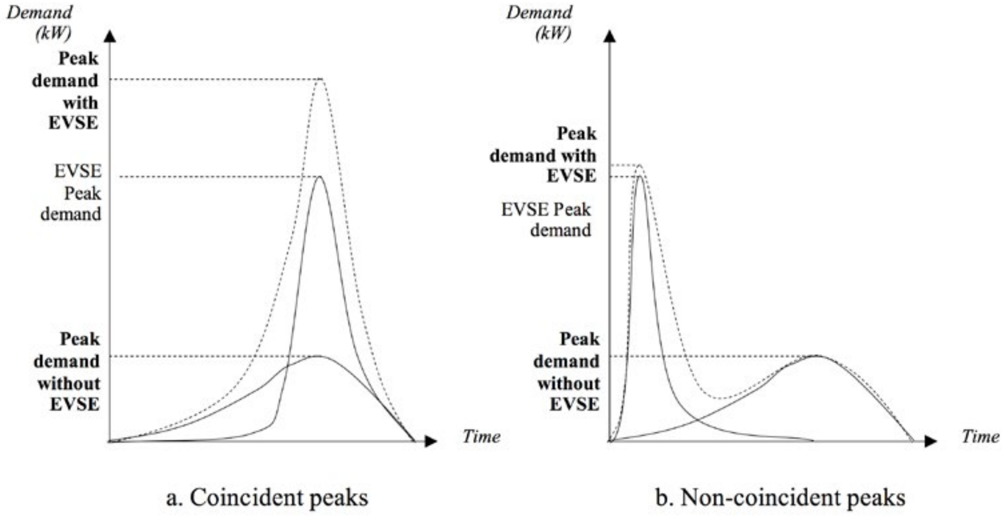
Table 2.4 Monthly demand charges ($) for each commercial charger type (on a commercial electricity tariff)

Charger Type	Power (kW)	**Total demand charge ($/month)** at U.S. general avg. of $8.62/kW	**Total demand Charge ($/month)** at U.S. EVSE avg. of $13/kW
Level 2 (standard)	6.6	57	86
Level 2 (maximum)	19.2	166	250
Level 3	50.0	431	650
Level 4	150.0	1,293	1,950
Level 5	350.0	3,017	4,550

The demand charge rises proportionally for additional chargers, since it depends only on maximum demand. Four 50kW EVSE at a single station will incur a charge of $1,724, assuming that all four EVSE are delivering maximum power simultaneously at least once a month (200 kW). Four 50kW EVSE operating in different locations, all with separate contracts, would incur four individual demand charges (4 x 50kW) of $531 each—again, a total of $1,724. A Level 5 station with ten charging poles, all of which are simultaneously in use for at least one 15-minute period each month, would incur demand charges *alone* totaling $45,500 per month or $546,040 per year.

The *marginal* cost incurred by an EVSE owner, who also purchases electricity for other purposes on the same contract, is more complex. It depends on knowing the difference between the demand charge that would be incurred without the EVSE (i.e. during the owner's regular operations), and the demand charge incurred with it. This figure is determined by whether the site host's peak demand *with* the EVSE coincides with peak demand *without* it. Consider a newly installed 50kW EVSE that reaches peak capacity at least once a month. If the EVSE peak demand, and peak demand from other operations, are coincident (Figure 2.1a), the site host would simply add 50kW to its peak demand. If it is not coincident (Figure 2.1b), because charging is only permitted outside business hours, or on days when air conditioning is not in use, the marginal demand charge would be less, and could even be zero if the peak demand with EVSE is less than the peak demand without it. A site host might incur consumer backlash and lose revenue by restricting charging to off-peak periods, however, our model assumes the two loads are fully coincident (i.e. that the marginal demand charge is 100%), but this scenario may not always be the case and the actual impact on costs can be lower.

Figure 2.1 Marginal peak demand from adding EVSE to an existing demand profile



How much of the cost of demand charges can be recovered depends not only on the percentage of time the charger is utilized, but also on the relative size of fixed and variable electricity costs. Very high demand charges can dominate the economics of underutilized DCFC stations, while operators' marginal revenues depend on the kWh of electricity sold per unit time—which is higher for more powerful stations. Thus, the cost of the power itself as opposed to the demand charge is comparatively small for a high-powered DCFC operating on a tariff with high (fixed) demand charges (per peak kW) and low (variable) electricity rates (per kWh). The revenue flow depends on utilization, exposing the operator to substantial downside risk of not being able to recover the fixed demand charge through revenues. Conversely, a charger with low demand charges and high electricity rates would suffer proportionally less from low utilization rates, since the monthly bill would be more closely correlated to the actual volume of electricity used[68] .

Commercial EVSE are typically self-service devices, meaning that in most cases they include some form of secure authentication system, payment system, and Internet/network connection (which can also provide the equipment operator and/or utility with real-time utilization data). These services come at additional costs—network connection fees and payment processing fees—which may vary from $100-$900 per charger, per year, depending on the equipment manufacturer, charger type, and service provider.[69]

Other incidental costs of ownership include maintenance and warranty/insurance costs, which vary according to charger type and location. Level 2 chargers are subject to both warranty and maintenance costs of about $400 each per year, according to documentation from EV Connect[70] and NRG.[71] Maintenance and warranty are typically more expensive for faster, commercial chargers with components under greater physical strain and at greater risk of vandalism or other physical damage. DCFC maintenance costs are estimated at $300-$3,000 annually, averaging $2,500 per year.[72] ChargePoint documentation places a 5-year warranty and maintenance package for 9 DCFC and 8 Level 2 chargers at $269,269, or $53,854 per year.[73] Documentation from Recargo puts maintenance for 11 DCFC and 7 Level 2 chargers at $95,000 over 5 years, implying $19,000 per year and $1,473 per DCFC.[74] In light of the substantial variation, this analy-

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[68] Fitzgerald, G. and C. Nelder. 2017. "EVGo Fleet and Tariff Analysis. Phase 1: California."

[69] Smith, M. and J. Castellano. 2015. "Costs Associated with Non-Residential Electric Vehicle Supply Equipment."

[70] EV Connect. 25 November 2015. "Electric Charging Highway Corridor 1." Submission in response to California Energy Commission GFO-15-601: DC Fast Chargers for California's North-South Corridors.

[71] NRG. 25 November 2015. "Electric Charging Highway Corridor 1." Submission in response to California Energy Commission GFO-15-601: DC Fast Chargers for California's North-South Corridors.

[72] Neubauer, J. and A. Pesaran. 2013. "A Techno-Economic Analysis of BEVs with Fast Charging Infrastructure". Presented at the 27th International Electric Vehicle Symposium and Exhibition, Barcelona, Spain. 17-20 November 2013.

[73] ChargePoint. 25 November 2015. "Electric Charging Highway Corridor 1." Submission in response to California Energy Commission GFO-15-601: DC Fast Chargers for California's North-South Corridors.

[74] Recargo. 25 November 2015. "Electric Charging Highway Corridor 1." Submission in response to California Energy Commission GFO-15-601: DC Fast Chargers for California's North-South Corridors.

sis assumes relatively high maintenance and warranty/insurance costs of $2,500 each per year for DCFCs.

Once the demand charge, electricity charge, network fees, insurance and maintenance are taken into consideration, making an operating profit on EVSE (i.e. excluding capital costs) can require marking up the per-kWh price of electricity substantially at the point of sale. Ensuring life-cycle profitability (including capital costs) will require a further markup to cover the installation, equipment, and utility upgrade costs described in the preceding section. Returns-to-scale may help to offset some capital costs: while facilities with greater numbers of chargers incur proportionally higher demand charges, a multi-charger station might incur lower per-charger capital costs than a standalone charger, since utility service extensions and transformer upgrades will typically only be required once for the whole facility.

In summary, the cost of power from a fast charging station will be higher than that from a Level one or Level 2 unit, unless the owners of the fast charging stations can find ways to drive up utilization rates and maintain those rates across time.

2.3 **Modeling Charging Economics**

We will now use a simple financial model to take a closer look at the economics of charging. We use fixed cost estimates from the available literature and variable costs from actual electricity rates. Revenue estimates are a function of utilization rates and load profile, and measured in $ per kWh. Note that not all EVSE operators will choose to bill their customers by kWh. They may, for instance, establish an hourly fee, or offer a monthly subscription service, or a combination of both. Since the variable cost of electricity is expressed in $ per kWh terms, however, revenues are denoted similarly. A markup is applied by the EVSE owner on each kWh of electricity at the point of sale. This is described below as the “final price.” For instance, if electricity costs the EVSE owner $0.14 per kWh on average and the markup required for the project to cover all her costs is $0.13 per kWh, he will need to charge a minimum final price of $0.27 per kWh to break even.

Residential EVSE refers to Level 1 (1.4kW) and Level 2 (here assumed to be 6.6kW, i.e. with no upgrade), and is subject to residential electricity rates. The results below present the net costs/savings of residential EVSE over 10 years relative to the cost of fuel for an average ICE (24 mpg) and an efficient ICE (40 mpg), estimated $2.50 per gallon, which is admittedly low compared with June 2018 prices.

Commercial EVSE refers to Level 2 (6.6kW), Level 3 (50kW), Level 4 (150kW), and Level 5 (350kW), and is subject to commercial electricity rates. The summary figures for commercial EVSEs in Figures 2.2 and 2.3 chart breakeven final electricity price needed for the charging system to post a net present value (NPV) of zero, for various estimates of utilization and the number of chargers per site. In Figures 2.4a and 2.4b, the NPV of charging stations under base case assumptions is calculated for different capital cost scenarios.

Base Case

The base case assumptions (see Appendix A.2) are calibrated to represent realistic, but conservative estimates, erring on the side of higher EVSE costs. The base case scenario for residential charging assumes uniform electricity rates with no ToU rates, no smart charging and no seasonal pricing, and a utilization rate that reflects the daily average electricity consumption of one EV (see Table 2.1). The base case scenario for commercial charging assumes third party ownership of charging infrastructure, and the owners assume liability for grid infrastructure upgrades; utilization rates are low at 10% (equivalent to 2 hours 24 minutes of charging per day); we use mid-range capital costs; and existing federal and state subsidies are included.

There have been other efforts to assess EV penetration and their impact on energy use.[75] A Rocky Mountain Institute study of EVGo data use a similar methodology, ranging from "business as usual" scenarios with low- and high-EV growth, to high-EV growth scenarios with increased autonomous

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[75] National Grid. 2017. "Future Energy Scenarios." http://fes.nationalgrid.com/media/1253/final-fes-2017-updated-interactive-pdf-44-amended.pdf

vehicle penetration.[76] While the scenario approach may be useful in this context for understanding "the big picture," it provides limited insight into the underlying economics. The approach taken here, therefore, is to manipulate key variables independently with a view to understanding which factors are most important.

For *residential charging*, the model is run for the base case; and for several alternatives including: ToU rates with an off-peak rate of $0.08 per kWh, and various partial-peak and peak rates ranging between $0.22-$0.35 per kWh (adapted from PG&E's EV Rate A[77]), accompanied by a 90% shift in the load profile to off-peak periods; and for higher and lower capital costs. For *commercial charging*, the model is run for a range of utilization rates; numbers of EVSE per site, and higher and lower capital costs.

2.3.1 **Results of the Analysis**

Level 1

Level 1 charging is modeled using both (a) uniform electricity rates and (b) ToU rates in which the consumer shifts 90% of demand to off-peak periods, benefiting from lower off-peak rates. There are no capital costs associated with Level 1 charging. The cost of electricity under uniform rates is $0.1759 per kWh; and the average cost of off-peak electricity under ToU rates is considerably lower, at $0.1245 per kWh. The resulting 10-year savings vis-à-vis "efficient" (40 mpg) and "average" (24 mpg) ICEs are detailed in Table 2.5. In the base case scenario, a Level 1 user would pay $305 more for power than an owner of a 40 mpg ICE would pay for fuel (a $2.50 monthly premium), but $4,622 less than an owner of a 24 mpg ICE (saving $38.50 per month). If the Level 1 user pays ToU rates for their electricity, the average rate paid for their EV charging falls as a result, saving almost $2,000 over a 40 mpg ICE and almost $7,000 over a 24 mpg ICE.

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[76] Fitzgerald, G. and C. Nelder. 2017. "EVGo Fleet and Tariff Analysis. Phase 1: California."

[77] Time-of-use rates adapted from Pacific Gas & Electric EV Rate A. 2017a. https://www.pge.com/tariffs/tm2/pdf/ELEC_SCHEDS_EV.pdf

Taken together, these results demonstrate that Level 1 charging is competitive with fueling today's efficient ICEs, assuming a uniform tariff. If we assume ToU rates, Level 1 charging provides significant savings over even the most efficient ICEs. This analysis, of course, ignores the opportunity cost of slow charging relative to other, faster-charging, options, and to the comparatively fast refueling of an ICE at a gasoline pump. As noted above, there is clearly a value associated with refueling a car more quickly—and it is quite possible that this value will negate some or all of the cost advantages of slow, or even fast, charging. One of the challenges for future analysts will be to determine this value.

Table 2.5 Residential Level 1 charging competitiveness of a BEV

Level 1	Uniform Rates	ToU Rates
Lifetime savings vs. 40mpg ICE	($305.50)	$1,945.36
Lifetime savings vs. 24mpg ICE	$4,622.58	$6,873.45

Level 2

Table 2.6 examines the equivalent analysis for residential Level 2 charging, this time including variations in capital costs (lower for newer houses that require no circuitry upgrades, higher for older houses that require extensive infrastructure upgrades). The base case assumes $1,000 in equipment costs, and $1,354 in installation costs, with no other associated costs except the purchase of electricity. Of immediate note is that Level 2 charging is not presently competitive with an efficient 40 mpg ICE regardless of capital cost (ranging from $1,300 to $14,000 more expensive, depending on capital costs). It is $2,200-$3,600 cheaper than a 24 mpg ICE for low or medium capital costs. If higher capital costs are included, that result flips and Level 2 charging is more expensive. As with Level 1 charging, with a 90% shift to off peak periods, ToU rates combined with low capital costs bring down the average cost of electricity, such that Level 2 charging is almost $1,000 cheaper than running a 40 mpg ICE and almost $6,000 cheaper than a 24 mpg ICE. On a levelized basis, a Level 2 residential system under base case assumptions costs $0.23 per kWh. When ToU pricing is available, the levelized cost falls to $0.15 per kWh.

Table 2.6 Residential Level 2 charging competitiveness

Level 2	**Uniform Rates**			**ToU Rates**
	Modern House (Low Capital Costs)	Average House (Moderate Capital Costs)	Older House (High Capital Costs)	Modern House with ToU Rates
Lifetime savings vs. 40mpg ICE	($1,295.50)	($2,659.50)	($13,946.50)	$955.36
Lifetime savings vs. 24mpg ICE	$3,632.59	$2,268.58	($9,018.41)	$5,883.45

2.3.2 **Commercial Charging**

Commercial charging is more complex, since the model must account for the cost of electricity to the operator of the charging facility, as a function of energy and demand charges, *as well as* the revenue generated through electricity sales. As detailed in Appendix A.2, electricity prices are assumed to rise at a rate of 3% per annum. The cost of financing is given as 8%, a realistic assumption, given the potentially high-risk nature of investment in charging infrastructure. Fuel costs for a 40 mpg ICE are $0.169 per kWh-equivalent and for a 24 mpg ICE, $0.282 per kWh-equivalent.

Figure 2.2 Response of breakeven price ($ per kWh, zero NPV) to various levels of utilization, compared to equivalent cost for 24mpg and 40mpg ICEs. L2 Res = levelized electricity cost for a Level 2 Residential system.

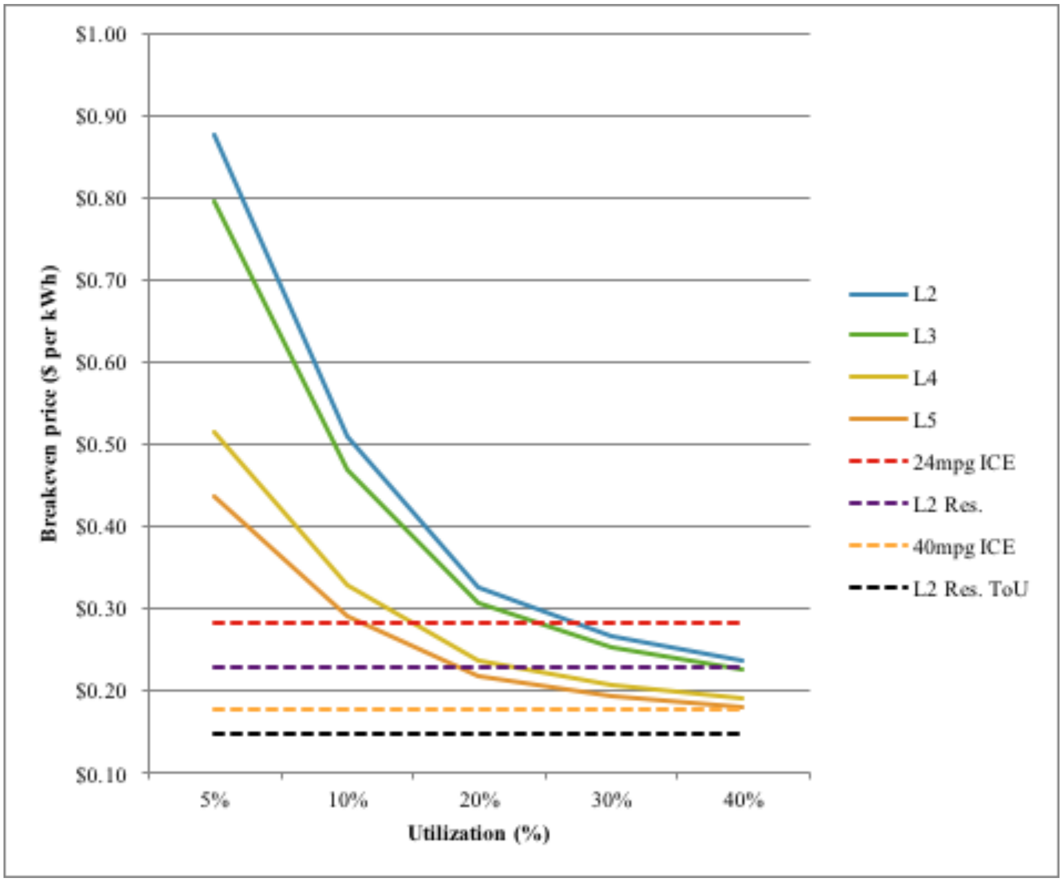

Figure 2.2 charts the “breakeven price” per kWh that the commercial operator must charge in order to break even on their investment (i.e, zero NPV) for different levels of utilization. Level 4 and Level 5 EVSE perform far better on breakeven price ($0.30 - $0.50 per KWh) than Level 2 and 3 ($0.80 - $0.90 per KWh) for lower levels of utilization. This is because revenue from greater kWh electricity sales for a given level of utilization more than offsets the higher capital costs and demand charges associated with higher-powered equipment. At Level 5 (350kW), 10% utilization corresponds to 420 kWh of energy sold per charger per day; seven times more than Level 3 (50kW) at just 60 kWh per day. For higher levels of power, a given level of utilization produces more additional revenue than additional cost, hence lowering the average margin the operator must make to break even.

At progressively higher levels of utilization, the breakeven electricity price falls steeply. This is in line with findings in other studies that utilization rates are a key determinant of profitability in the absence of alternative or indirect sources of revenue.[78] At 20% utilization, the breakeven price for Level 4 and Level 5 is comfortably below the equivalent for an average 24 mpg ICE and competitive with home charging. At 30% utilization and above, all varieties of public charging are cheaper than the 24mpg equivalent, and at 40% utilization, Level 4 and 5 are very nearly competitive with an efficient 40 mpg ICE.

No form of commercial charging is competitive with home charging under ToU rates. The shape of the curve (albeit with only five data points per charger type) suggests decreasing returns to utilization. This is because for higher levels of variable revenue, the marginal profit from each additional kWh sold offsets a decreasing proportion of the total cost of the charging infrastructure.

The analysis in Figure 2.2 is not representative of reality in two ways. First, it models only breakeven pricing, with no financial return on the investment. For EVSE to be a viable investment in private capital markets, a higher rate of return would be required. Furthermore, at 5% utilization, most analogous to today's market, the breakeven prices are worryingly high—from $0.44 per kWh (Level 5) to $0.87 per kWh (Level 2). Twenty percent utilization (4 hours 48 minutes per day) is more difficult to achieve than it sounds, particularly for higher-powered chargers. A single Level 4 (150kW) charger operating at 20% utilization and delivering an average of 13.65 kWh per charge (the average EV owner's daily usage) would need to deliver 53 such charges a day. Level 4 and 5 commercial charging are not cost competitive with Level 2 home charging, for utilization rates below below 20%. Commercial fast-charging stations will therefore need to develop business strategies that will keep utilization rates above the 20% threshold, if they are to draw customers away from their home chargers.

Second, the analysis does not include the opportunity cost of time spent waiting for the vehicle to charge—a potential, but important concern for

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[78] Snyder, J., D. Chang, D. Erstad, E. Lin, A. Falken Rice, C.T. Goh and A. Tsao. 2012. "Financial Viability of Non-Residential Electric Vehicle Charging Stations." UCLA Luskin School of Public Affairs. See also Bryant, J and B. Luxenburg. 2017. "The Role of Charging Infrastructure in Electric Vehicle Adoption."

many consumers. Rather than seeking to empirically measure the opportunity cost, we opted to estimate the maximum value of time consistent with an individual preferring commercial EV charging over (a) gasoline refueling and (b) residential charging, in cases where commercial EV charging is cheaper. We assume there is no opportunity cost of time for residential charging, since overnight charging in a home garage places almost no constraints on the user's alternative uses of that time. To calculate this maximum, we find the difference between the cost of commercial charging ($ per kWh) and cost of refueling/residential charging for different levels of utilization, then scale it by the charging rate (minutes per kWh) to arrive at a $ per minute threshold above which commercial EV charging ceases to make economic sense due to the length of time it takes.

Table 2.7a Maximum cost of time (in $ per minute) for a user to prefer commercial EV charging to refueling a 24 mpg ICE, at breakeven charging prices

Utilization	Level 2	Level 3	Level 4	Level 5
5%	-	-	-	-
10%	-	-	-	-
20%	-	-	$0.11	$0.37
30%	$0.00	$0.02	$0.19	$0.52
40%	$0.01	$0.05	$0.23	$0.59

Table 2.7b Maximum cost of time (in $ per minute) for a user to prefer commercial EV charging to Level 2 residential charging with no ToU rates, at breakeven charging prices

Utilization	Level 2	Level 3	Level 4	Level 5
5%	-	-	-	-
10%	-	-	-	-
20%	-	-	-	$0.07
30%	-	-	$0.06	$0.21
40%	-	$0.00	$0.10	$0.28

In Table 2.7a, comparing against a 24 mpg ICE, Level 3 charging is only viable if the consumer values time at less than $0.02-$0.05 per minute depending on the level of utilization. In other words, a motorist who considers their time to be more valuable than this would prefer to avoid spending time charging their vehicle and simply use a gasoline car instead. Since a 50 kWh Level 3 charge can take over an hour and gasoline refueling takes just a few minutes, the motorist valuing their time at $0.05 per minute may be willing to pay over $3 extra per session to refuel with gasoline and recover the time lost in waiting for their EV to charge, even though EV charging is nominally cheaper. For Level 4, the motorist valuing their time above $0.11-$0.23 per minute would theoretically pay a premium of $1.65-$3.45 per 15-minute session to refuel with gasoline instead. For Level 5 charging, those valuing their time above $0.37-$0.59 would pay $1.85-$2.95 per five-minute session to be able to refuel with gasoline. The analogous figures when comparing against residential Level 2 charging (with no ToU rates) are $0.00 for Level 3, $0.06-$0.10 for Level 4, and $0.07-$0.28 for Level 5 (see Table 2.7b). While entirely theoretical, this finding suggests that for motorists placing a significant premium on their time, commercial fast charging may still not be the preferred option, even when cheaper than the gasoline equivalent, due to the time taken to recharge. Further, as might be expected, the lower time-value thresholds associated with residential Level 2 charging hint that it might be an even greater competitor to commercial fast charging than fueling an ICE at gasoline station. A useful avenue for future research would be to gather empirical data on the value of time from actual and potential EV users to establish whether it is within the ranges given here and assess the impact on charging economics.

Another avenue for cost reduction is simply reducing per-charger costs of each EVSE by adding more chargers to a given station to take advantage of the already-sunk investment in transformers and utility service upgrades. This will occur if the per-unit cost savings are greater than the costs from the larger demand charges and inclining block rates incurred by adding another charger (see Section 2.2).[79] Each new charger must have equal or greater utilization than the existing charger(s). At base case assumptions

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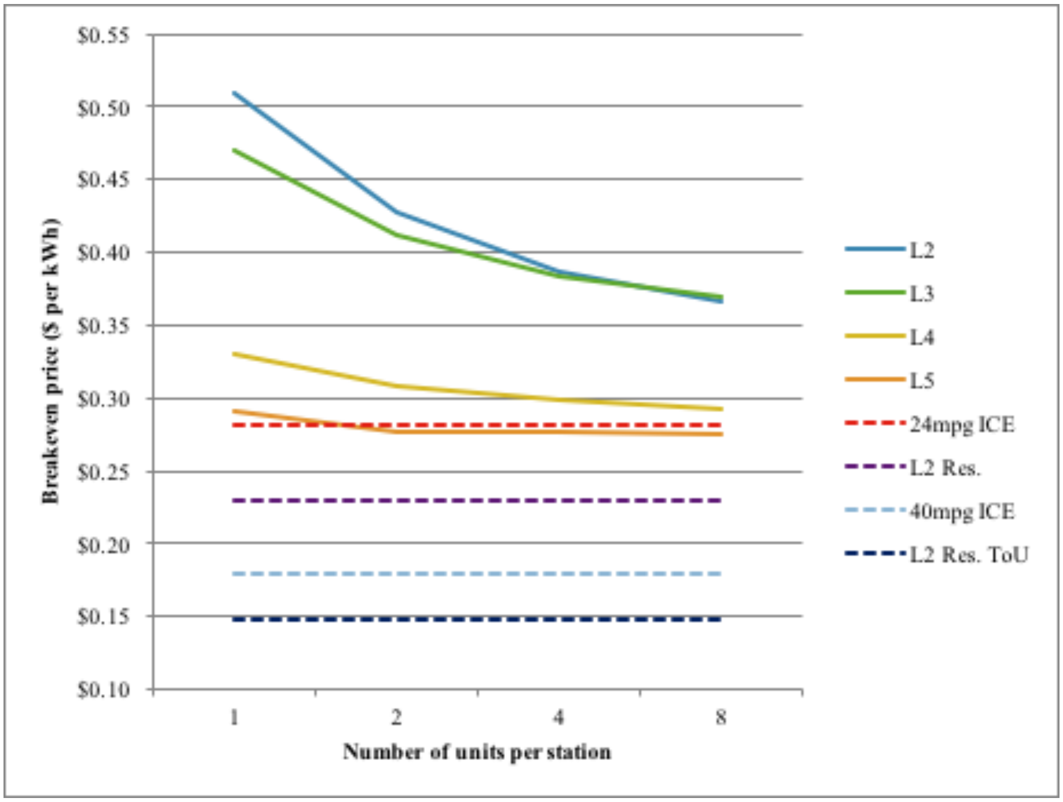
[79] Hall, D. and N. Lutsey. 2017. "Literature Review on Power Utility Best Practices Regarding Electric Vehicles."

(with utilization at 10%), there are indeed returns to scale. Since for less powerful chargers, utility service extension and transformer costs are a greater proportion of total capital costs, sharing those costs across multiple chargers brings down the average cost proportionally more, as observed in Figure 2.3. The effect is not as dramatic as in the high utilization cases, and scale alone is not sufficient to bring breakeven prices below $0.37 per kWh for Level 2 and Level 3 for 8 units. At 8 units, Level 4 and Level 5 are roughly competitive with a 24mpg ICE, but nowhere near the $0.18 per kWh comparable with a 40mpg ICE, or the $0.23 per kWh comparable with the levelized cost of a Level 2 residential system.

Figure 2.3 Response of breakeven price ($ per kWh, zero NPV) to number of units in EV charging station. L2 Res = levelized electricity cost for a Level 2 Residential system.



The need to increase the number of daily charges at larger stations of 4+ units in order to bring breakeven cost down will be challenging. A 4-unit station of Level 4 chargers would need to attract 211 average (13.65 kWh) charges a day, or seventy 100-mile (37 kWh) charges a day, to undercut the levelized cost of Level 2 residential charging. While this may be likely in a high-BEV penetration future, in the short-to-medium term it will remain a challenge and suggests that investments in multi-unit high-powered EVSE stations today will likely face net losses, in the next decade as EV deployment remains low.

Figure 2.4a *NPV for commercial charging infrastructure at $0.169 per kWh (competitive with 40mpg ICE). In high, medium and low capital cost scenarios.*

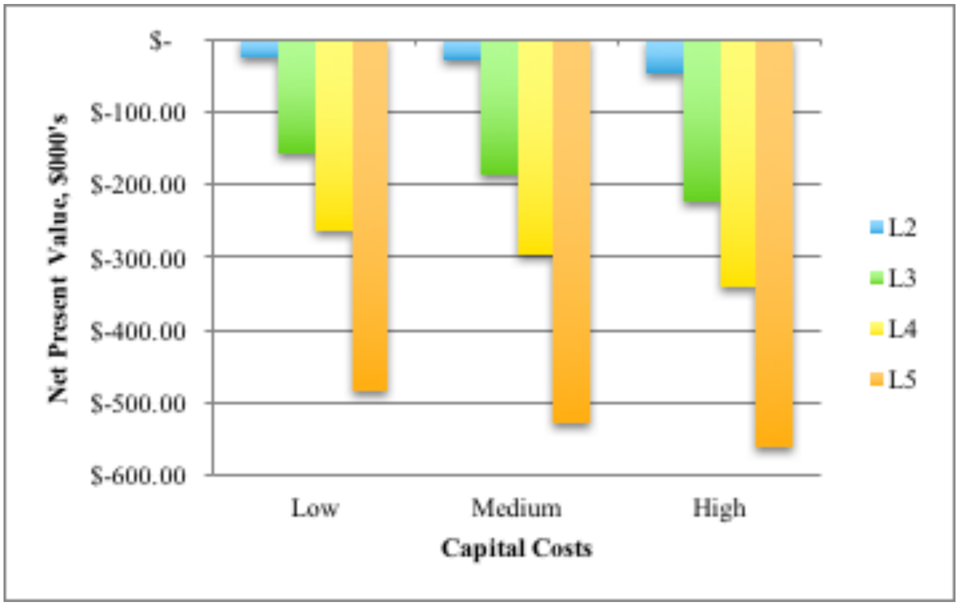
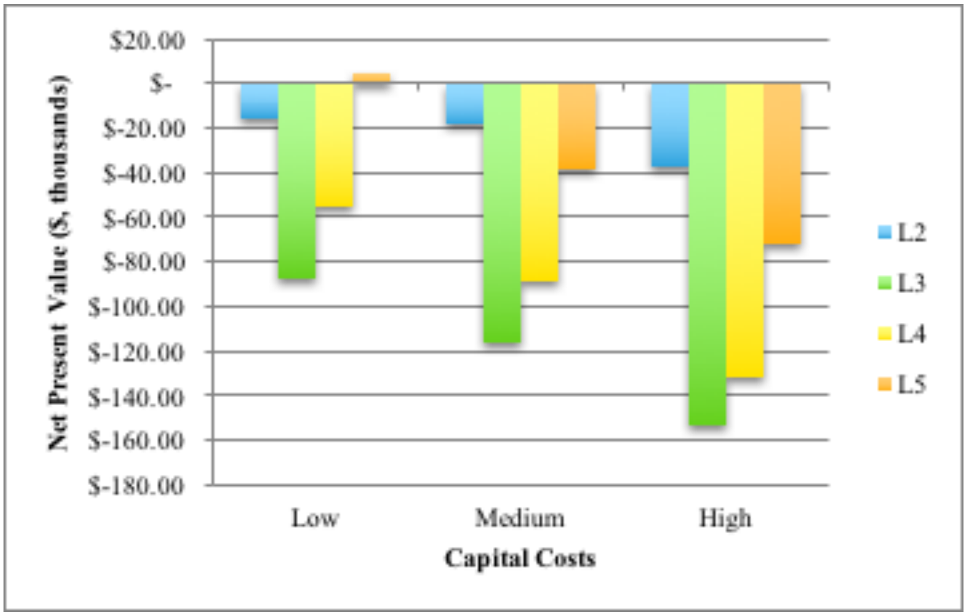


Figure 2.4b NPV for commercial charging infrastructure at $0.282 per kWh (competitive with 24mpg ICE). In high, medium and low capital cost scenarios.



Breakeven price analysis does not tell the full story. At 10% utilization, almost all varieties of commercial charging post a negative NPV for low, medium, and high capital costs, and for electricity sales priced at $0.169 per kWh (40 mpg ICE equivalent) and $0.282 per kWh (24mpg ICE equivalent)) (see Figure 2.4a and 2.4b). The energy charge for electricity is $0.1447 per kWh and demand charges are applied as an additional cost.

2.3.3 **Pricing Models**

Williams and DeShazo's (2014) Monte Carlo simulation suggests that Level 2 commercial charging, at 6.25% utilization, and a final price of $0.33 per kWh, recovers only $1,000-$2,000 in capital investment over the lifetime of the facility. The investor would need to quadruple utilization to 25% to recover $9,000 in capital investment. While Williams and DeShazo use different assumptions than those used in our analysis, their results are approximately the same. They also use a Monte Carlo simulation to compare pay-per-kWh systems to pay-for-time and monthly subscription pricing strategies, as an alternative means of recovering costs. In the simulation's base case, setting prices by kWh yields an average Level 2 NPV of $264 per unit. Setting prices by time ($1.50 per hour) yields a negative average NPV of -$1,387. Setting a relatively high $45 per month subscription fee yields an average NPV of -$910. [80] So, not only does per-kWh charging appear more economically sustainable, fee structures with a larger fixed component favor heavier users with larger batteries; under a subscription or time-based model, lighter users with smaller, slower-charging batteries may confront much higher per-kWh charging costs.

A subscription fee alone appears insufficient to replace per-kWh pricing. Assuming the owner must charge $0.30 per kWh to break even, a $45 per month subscription fee would allow for the subscriber to use a maximum of 150 kWh per month. At 13.65 kWh per day daily usage, this would cover only 11 days. To cover the monthly electricity consumption of 409 kWh implied by average daily usage, the subscription fee would have to be over

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[80] Williams, B. and J.R. DeShazo. 2014. "Pricing Workplace Charging: Financial Viability and Fueling Costs". Journal of the Transportation Research Board **No. 2454: 68–75. doi: 10.3141/2454-09.**

$100. Even then, customers would have an incentive to charge as much as possible past that point, given the marginal cost to them would be zero.

While uncertainty in day-to-day utilization rates at low EV penetration levels remains a large problem, the use of a subscription fee *combined* with lower cost-per-kWh pricing may be sustainable, depending on the size of both the fee and the total demand. In principle, combining the two would serve as a hedge against the uncertainty around utilization rates, and assure EVSE operators of a fixed minimum monthly revenue stream to help recover the cost of demand charges.

Selling per-kWh electricity, in some jurisdictions across the United States, requires the company in question to be registered and approved as a regulated utility, a potentially long and bureaucratic process. Furthermore, it is not at all clear, how utility regulators will set prices at commercial fast charging stations. Heretofore, these stations have been used as loss leaders, to attract consumers to purchase electric vehicles, but at some point in the future, they will have to be able to stand on their own commercially.

Further research is clearly needed to understand how charging stations will price their product. Studies to date have relied on stated preference methods that are likely to suffer from cognitive and strategic biases, such that do not reveal true willingness-to-pay for EV services.

Prospective EV owners in the United States rank availability of commercial charging infrastructure as second only to (subsidized) pricing when considering a purchase.[81] While the above analysis has shown that commercial Level 4 and 5 EVSE can be competitive on breakeven electricity cost with residential Level 2 charging at utilization levels above 20%, commercial Level 2 and Level 3 EVSE do not meet this threshold until utilization reaches 40%. This suggests that commercial charging, as it is currently available, (predominantly Level 2 and Level 3) will not be able to compete with residential charging on price. The advantage of residential charging increases under most ToU tariffs. As forementioned, some consumers may place a high value on the time taken to refuel their vehicles in public

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[81] Carley, S. and Krause, R. "Intent to Purchase a plug-in electric vehicle: A Survey of early impressions in large U.S. cities." https://pdfs.semanticscholar.org/24b8/f4ea90b2f034c4ff-fae8df047174d4fd3f53.pdf

places (as opposed to overnight, at home) and may not be willing to meet the breakeven price for even the fastest charging options. The size of the market for fast charging, and the prospects for increasing utilization rates at Level 3-5 stations, will remain uncertain until this time value is better understood. This is an important question for further research to address.

2.3.4 **Summary**

The economics of commercial EV charging are not straightforward, owing to the number of parameters that can change from site to site, a lack of standardized data on capital costs, demand charges and load profiles, and persistent uncertainty on the determinants of utilization. The sheer variation in circumstances in which commercial EVSE are installed means that there is substantial variation in the costs associated with equipment installation, wiring, trenching, signage, permitting, labor costs, utility service upgrades, and transformer upgrades that are highly context-dependent. Although comprehensive studies of Level 2 charging behavior are available, there is much greater uncertainty around the predictors for Level 3-5 stations, due in part to the proprietary nature of most load profile and utilization data. The variation in costs from one location to another could make it extremely difficult, for governments looking to promote EV ownership, to artificially regulate prices at commercial charging stations.[82]

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[82] While beyond the scope of this paper, this is a potentially crucial subject for public utility commissions to address in the coming years. It would be administratively costly to regulate prices at individual stations, and it would be equally problematic to set one kWh price for all stations given the sensitivity of charging station economics to utilization, which itself varies widely. Options open to regulators include the regulation of retail charging prices, allowing market competition or a combination of both. The regulatory approach taken will affect the viability of these stations, particularly for fast chargers competing against both gasoline and home charging.

2.4 Load Management for Large-Scale EV Integration

In the preceding section, we pointed out that ToU tariffs could significantly reduce the cost of Level 2 home charging and that regulators will be pushed to develop sophisticated versions of ToU rates to encourage the penetration of electric vehicles. Further, advocates describe scenarios in which fleets of BEVs serve as electricity storage units for the grid—repowering their batteries during off-peak time and then selling a portion of this power back to the grid during peak hours. Electric vehicles could theoretically become an integral part of grid management. We examine first the potential impact of EVs on electricity demand patterns and then briefly assess the factors that will affect the use of EVs as sources of power storage.

In much of the United States, regional Independent System Operators (ISOs) coordinate and oversee electricity markets, in which power is purchased by distributors through day-ahead bidding and/or spot markets through a system of locational pricing that reflects generation and transmission costs for different nodes in the power network. The cost of electricity, usually at its lowest in the early hours of the morning, varies throughout the day, typically rising to a peak from roughly 4:00-8:00 p.m. (earlier, in the summer) as customers return to their homes and turn on lights, heating/air conditioning and appliances. Figure 2.5 plots median hourly prices across all nodes from 2008/9-2014 for the four ISOs for which relevant data was available—NYISO (New York), MISO (Mid-continent), PJM (East), and ISONE (New England). Winter peaks occur between 4:00-8:00pm and significantly higher summer peaks occur around 3:00-4:00pm.[83]

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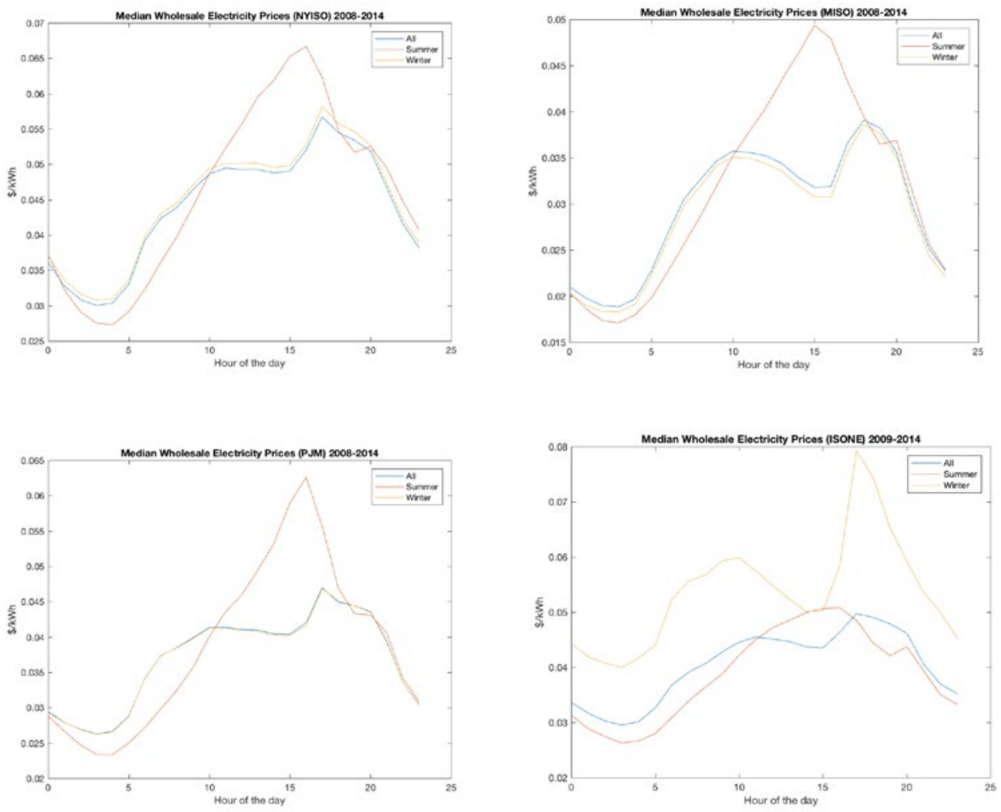
[83] ISO New England is a special case. While there is indeed a muted summer peak around 3:00-4:00pm, the winter peak at around 6:00pm is much higher. Reasons for this might include different demand patterns and pricing rules, cheaper summer peaking units and winter fuel supply constraints (primarily natural gas) driving higher prices.

Figure 2.5 Median hourly locational marginal prices (LMPs) for four Independent System Operators (ISOs) in the United States.[84]



High concentrations of EV home charging during peak periods (e.g. late afternoon in a residential neighborhood in which 25% of residents charge their EVs daily) can overload local transformers. Without measures in place to shift individual charging loads away from peak times, utilities would find themselves having to purchase ever-greater peak capacity to meet EV demand, and increase their local distribution capacity. Not only would this increase the cost of electricity; it would also hamper efforts to decarbonize the grid by increasing the use of highly-responsive, high-capacity peaking generators—typically natural gas-fired.

There are several potential solutions to this problem. The most obvious are policies designed to incentivize customers to shift demand away from peak times as a means of (a) reducing the need for utilities to purchase peak capacity and (b) taking advantage of excess base-load capacity at

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[84] Based on locational marginal price data (some unpublished) from Electricity Power Markets LMP Dataverse. Accessed August 2017. https://dataverse.harvard.edu/dataverse/EPMD. Raw data is publicly available from all ISOs.

night and in the early morning. This is distinct from dynamic/real-time pricing, which varies continuously (usually on an hourly basis) and reflects changes in the wholesale price of electricity and network congestion in real time. The most compelling argument against ToU rates is that they do not reflect the actual cost of power at any given time. If EV penetration grows there will be growing pressures to move to dynamic pricing to reflect actual rather than projected costs. In a world seeing 20-30 percent EV deployment rates, both real time pricing options and alternatives to present day demand charges will be a primary focus of utility regulators. This is an important question, but one to be addressed in future research.

Another element in successfully managing EV loads is smart metering, allowing communication between EVs and utilities/ISOs. These meters will complement the use of price signaling by allowing the charging of multiple EVs in the same network to be sequenced over time to avoid overloading the local transformer, while still meeting the requirements of the EV owner. If we assume that a BEV owner charges his vehicle every evening, only drives the average number of miles per day, and uses a 6.6kW Level 2 charger, the car will only need two hours to charge over an eight-hour window. In such a case, "smart" charging (facilitated by smart meters communicating with a central load management system) could provide significant system benefits by smoothing the demand over the entire eight hours to reduce peak load on the local distribution circuit. In turn, utilities can make more efficient use of generation resources and reduce pressure on local distribution systems, particularly over the "last mile" of distribution in which transformer overload and congestion are more likely.

BEVs doubling as storage options for the grid using Vehicle-to-Grid (V2G) technology is technically a possibility, especially if average battery sizes increase, as we suspect they will. However, technical feasibility is not by itself sufficient to conclude that this scenario will happen. Owners of EVs with V2G capability would charge their cars during the night when the cost of power is low and sell it to the grid in the late afternoon and early evening when demand for power is highest. For this to occur, the BEV must be plugged into the distribution grid system during that time. Further, the vehicle's battery must be at least partially charged and the inverter will need to be run in reverse, since the battery's power would be DC and the local grid will only accept AC power. Finally, the car owner will not be selling power for free, since she will have paid something to recharge and will want to both recoup her investment *and* earn a profit or rate of return. Hence, the grid or local distribution utility will have to offer the equivalent of a feed-in-tariff for that power. If the tariff is set too low, BEV owners may forego this opportunity. All three conditions would need to be present at the same time: an EV plugged in at peak hours; a battery with surplus power; and an attractive feed-in tariff that will make the sale of power from the battery worthwhile.

3. Conclusion

The challenges facing EV deployment have become more tractable in recent years, but they are still considerable. The life cycle cost of ownership of BEVs has fallen substantially; further declines in installed battery prices below $300 per kWh may lead to genuine parity with ICEs in the next 5-7 years. Of far more consequence for sustainably scaling EV ownership is the cost-effective, efficient deployment of charging infrastructure. Standalone economic analysis of different charging options suggests that residential Level 2 charging, where available, can be the best option for most of an EV owner's charging needs, and that ToU rates (mostly for overnight charging) can bring down the average cost of electricity to below the equivalent fuel cost for an ICE. Unprecedented levels of investment and product development planned by almost all major OEMs clearly indicates that a much larger EV market is forthcoming.

The picture is less rosy for the commercial charging infrastructure required to serve this expanding market. DCFC charging (Levels 3-5) is exposed to much higher monthly demand charges and greater need for consistently high utilization to break even. The analysis has demonstrated that for levels of utilization above 20%, DCFC breakeven electricity prices can be competitive with gasoline prices. This is an important finding—but is made in the context of many unresolved regulatory and public policy issues, and very significant downside risks for underutilized infrastructure.

The debate over utility ownership of EV infrastructure is ongoing. The criteria for deciding whether public ownership and rate-basing the cost of charging infrastructure is the appropriate tool for developing this market, or whether charging infrastructure should be left entirely to the private sector, are unresolved. A further question is how utilities, third parties, and OEMs can most effectively coordinate/pool their respective expertise in a manner which preserves competitive dynamics, but optimizes EVSE charging decisions in the most socially efficient manner possible.

While there are uncertainties around the commercial penetration of electric vehicles, a future scenario in which governments agree to substantially decarbonize their economies will involve partial electrification of the transportation sector. There are differences of opinion on the rate at which this transition will occur, but there is clear technological and economic traction towards much greater reliance on electric vehicles. New rate designs, better smart metering and charging equipment technologies, and a charging infrastructure that is convenient and price competitive will need to be developed and implemented. These are difficult but achievable tasks.

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Appendices

A.1 **Lifetime EV Cost Modeling**

General

Miles per year	13,476
Useful life (years)	10
Electricity price ($ per kWh)	$0.1759
kWh used per mile (BEV/PHEV)	0.37

Vehicles

	ICE	**PHEV**	**BEV**
Model	Chevrolet Impala	Chevrolet Volt	Chevrolet Bolt
List price ($)	27,095	33,220	37,495
Conventional fuel economy (mpg)	26	42	-
Electric fuel economy (kWh/mile)	-	0.37	0.37
Annual maintenance costs ($)	1,000	1,200	500
Battery capacity (kWh)	-	18	60
Electric-only mode (%)	0%	70%	100%

A.2 Charging Infrastructure Base Case Model Assumptions

Financial

Cost of capital	8%
Electricity price, annual increase	3%
Demand charge, annual increase	0%
Fuel price, annual increase	3%

Electricity Prices ($/kWh)[85]

Residential[A]	0.1759
Commercial[B]	0.1447
Residential time-of-use (off-peak)	0.0800
Residential time-of-use (peak May-October)	0.3500
Residential time-of-use (peak November-April)	0.2700
Residential time-of-use (partial peak May-October)	0.2200
Residential time-of-use (partial peak November-April)	0.1759

A, B Energy Information Administration. 2017. "Electricity data browser."

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[85] Time-of-use rates adapted from Pacific Gas & Electric EV Rate A. 2017a. https://www.pge.com/tariffs/tm2/pdf/ELEC_SCHEDS_EV.pdf

EV Charger Specifications

	L1 Res.	L2 Res.	L2 Comm.	L3 Comm.	L4 Comm.	L5 Comm.
Power delivery (kW)	1.4	6.6	6.6	50	150	350
Full charge (hours)	48.2	10.2	10.2	1.4	0.5	0.2
Daily usage recharge (hours)	9.7	2.1	7.2	0.9	0.3	0.1
Utilization	41%	9%	10%	10%	10%	10%
Utilization growth/yr	0%	0%	10%	10%	10%	10%
Total chargers per station	1	1	1	1	1	1
Charge sessions/month	1	1	3	18	53	124

Load Profile	L1 Res.	L2 Res.	L2 Comm.	L3 Comm.	L4 Comm.	L5 Comm.
12am-6am	25%	25%	0%	0%	0%	0%
6am-9am	0%	0%	5%	5%	5%	5%
9am-12pm	0%	0%	10%	10%	10%	10%
12pm-3pm	0%	0%	15%	15%	15%	15%
3pm-5pm	0%	0%	15%	15%	15%	15%
5pm-7pm	25%	25%	30%	30%	30%	30%
7pm-9pm	25%	25%	20%	20%	20%	20%
9pm-12am	25%	25%	5%	5%	5%	5%

EV Charger Specifications, cont.

Capital Costs ($)	**L1 Res.**	**L2 Res.**	**L2 Comm.**	**L3 Comm.**	**L4 Comm.**	**L5 Comm.**
Equipment (per charger)	0	1,000[A]	3,842[B]	35,000[C]	50,000	100,000
Installation (per charger)[16]	0	1,354	3,108	22,626	22,626	22,626
Site preparation (per charger)	0	0	3,000[D]	12,500[E]	12,500	12,500
Utility service	0	0	4,000	17,500[F]	17,500	17,500
Transformer	0	0	5,698[G]	32,500[H]	40,000[I]	40,000

Variable Costs ($)	**L1 Res.**	**L2 Res.**	**L2 Comm.**	**L3 Comm.**	**L4 Comm.**	**L5 Comm.**
Maintenance (per year)	0	0	400	2,500	2,500	2,500
Insurance (per year)	0	0	400	2,500	2,500	2,500

Subsidies[K]	**L1 Res.**	**L2 Res.**	**L2 Comm.**	**L3 Comm.**	**L4 Comm.**	**L5 Comm.**
Equipment	0	0	1,000	15,000	15,000	15,000
Tax Credit	0	0	1,390	2,500	2,500	2,500

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