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A Techno-Economic Analysis of BEVs with Fast Charging Infrastructure

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Abstract

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gas emissions, but high upfront costs, battery-limited vehicle range, and concern over high battery replacement costs may discourage many potential purchasers. One proposed solution is to employ a subscription model under which a service provider assumes ownership of the battery while providing access to vast fast charging infrastructure. Thus, high upfront and subsequent battery replacement costs are replaced by a predictable monthly fee, and battery-limited range is replaced by a larger infrastructure-limited range. Assessing the costs and benefits of such a proposal are complicated by many factors, including customer drive patterns, the amount of required infrastructure, and battery life. Herein the National Renewable Energy Laboratory applies its Battery Ownership Model to address these challenges and compare the economics and utility of a BEV fast charging service plan to a traditional direct ownership option. In single vehicle households, where such a service is most valuable, we find that operating a BEV under a fast charge service plan can be more cost-effective than direct ownership of a BEV, but it is rarely more cost-effective than direct ownership of a conventional vehicle.

Keywords: Battery Ownership Model, fast charge, electric vehicles, total cost of ownership, range extension

1 Introduction

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gas emissions relative to conventional vehicles (CVs). However, in practice, high upfront cost, concerns over battery life and high battery replacement costs, and battery-limited vehicle range of today's BEVs may discourage potential purchasers. One proposed solution is to employ a subscription model that insulates consumers from the risks of battery degradation and provides access to fast charge infrastructure. Under such a scenario, drivers would purchase a BEV without a battery and pay a monthly subscription fee for access to service-provider-owned batteries and fast charge infrastructure.

Comparing this option to a traditional direct ownership, though, is not straightforward. As discussed at length in [1], computing the total cost of ownership (TCO) of BEVs under a direct ownership (DO) scenario itself is challenging. Adding a service provider and fast charging to the equation increases complexity via the need to account for fast charge infrastructure and quantify service provider economics.

With support from the Vehicle Technologies Office in the U.S. Department of Energy, the National Renewable Energy Laboratory has developed a vehicle total cost of ownership (TCO) calculator known as the Battery Ownership Model (BOM) to evaluate and analyze these and other challenges associated with the lifecycle economics of electric vehicles and advanced business strategies. The BOM accounts for vehicle and component costs, battery and fuel price forecasts, drive patterns, battery wear, charging infrastructure costs, purchase incentives, financing, ownership, and other criteria. Previously we applied this tool to the analysis of traditional ownership of BEVs [1] and plug-in hybrid electric vehicles [2] as well as to BEVs operated under a battery swapping service plan [3].

Herein we apply the BOM to compare the economics and utility of a BEV fast charging service plan option (SP-BEV) to traditional direct ownership of a BEV (DO-BEV) and of a CV (DO-CV). After briefly discussing our general approach to modelling TCO and computing the DO-CV and DO-BEV economics, we evaluate the SP-BEV via the following four steps: (1) identifying drive patterns best suited to this plan, (2) modelling service usage statistics for the selected drive patterns, (3) calculating the cost of different service plan options given these statistics, and (4) evaluating the economics of individual drivers under realistically priced service plans.

2 Total Cost of Ownership Calculation Approach

The methods and assumptions applied herein for computation of TCO are generally consistent with those in [1, 3] except when explicitly noted otherwise. The vehicle economics considered include vehicle and related infrastructure purchases, financing, fuel (gasoline and electricity) costs, non-fuel operating and maintenance costs, battery replacement, salvage value, and costs associated with a service provider when applicable. Battery degradation, charging strategies, and drive patterns play an important role in each of these elements as discussed in [1-3]. We use 398 real world longitudinal drive patterns from the Puget Sound Regional Council's Travel Choice Study (TCS) [4] to calculate vehicle usage and create battery duty cycles. The vehicles employed for this study are the same as those in [1, 3], where a variable drivetrain is adapted to a standard mid-size sedan platform to yield a 9 second 0–60 mph acceleration time and a specified range (Table 1). Both fuel and electricity consumption are calculated via simulation of the highway and urban driving dynamometer schedule weighted and combined to be representative of the U.S. Environmental Protection Agency window sticker rating [5] assuming a constant 300 W auxiliary load for accessories [6].

3 Direct Ownership Analysis

Prior to addressing the fast charge service provider cases, we analyze two traditional competing alternatives: DO-BEV and DO-CV. The TCO for each vehicle is computed over all 398 TCS drive patterns assuming a 2015 vehicle purchase year, 15 year analysis period, and 8% driver discount rate per the methods and assumptions in [3]. The CV analysis assumes the efficiency reported in Table 1 and the national average gasoline price forecasts as reported in the Energy Information Administration's (EIA's) 2011 high oil price scenario [7] (Figure 1). No range restrictions are placed on CV travel.

For the BEV analysis, we employ the Table 1 vehicle specifications for the 75-mile-range BEV utilizing a 100% maximum state of charge (SOC), as this was identified as the most cost-effective BEV solution when the cost of unachievable vehicle miles travelled (VMT) is high (e.g., single vehicle households) in [1] and is a reasonable representation of currently available BEV options. We evaluate three different battery manufacturing costs ($125/kWh, $300/kWh, and $475/kWh) that span the DOE's advanced battery cost targets [8] and several industry battery cost forecasts [9-11]. A 1.5 manufacturing-to-retail mark-up [12-14] is applied to calculate the price offered to the consumer or service provider. We assume no tax credits or other purchase incentives are available.

A 32 amp, 240 V charger is assumed installed at the driver's home for $1,200. Residential customer electricity price projections from the EIA's 2011 baseline scenario [7] (Figure 2) are employed. The amount of energy consumed is calculated based upon an 85% charging efficiency and the achieved annual VMT, which changes annually as a function of drive pattern and battery degradation.

Table 1. Vehicle specifications (all prices in 2012 dollars)

Vehicle	Electric Range (mi)	Maximum SOC	Engine or Motor Power (kW)	Battery Energy (kWh)	Vehicle Efficiency (kWh/mi)	2015 Vehicle Retail Price (w/o Battery)
CV	0	n/a	100	0	32 mi/gal	$17,687
BEV50	50	100%	79.7	16.6	0.332	$16,150
		95%	80.3	17.5	0.333	$16,161
		90%	80.8	18.6	0.334	$16,170
BEV75	75	100%	85.3	25.7	0.343	$16,252
		95%	86.3	27.2	0.345	$16,268
		90%	87.2	28.8	0.347	$16,285
BEV100	100	100%	91.1	35.4	0.355	$16,356
		95%	93.0	37.6	0.358	$16,390
		90%	94.4	40.0	0.361	$16,415

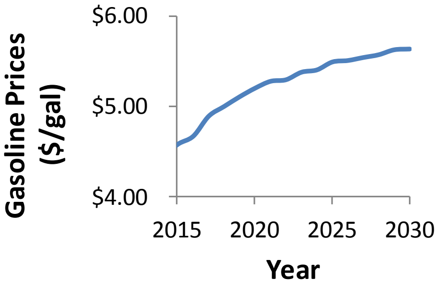

Figure 1. Employed gasoline prices (2012 dollars)

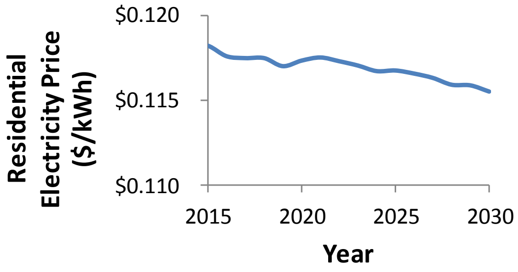

Figure 2. Employed residential electricity prices (2012 dollars)

Battery degradation is calculated using a high-fidelity life model [15] that projects capacity loss and resistance growth at the end of each service year based on the selected drive pattern, a just-in-time charge strategy, and national average environmental conditions. Minimum SOC is adjusted each year such that no less than 80% of beginning of life (BOL) power can be delivered at the end of charge depleting operation due to minimum voltage requirements, thus translating the effect of power fade to a reduction in available energy, and thereby vehicle range. In addition to calculating achieved VMT, we also leverage this capability to employ bounded, cost-optimal battery replacement schedules as originally proposed and examined in [1].

A cost is applied to unachievable VMT per the *high-cost* approach described in [1], which assumes that a CV is rented via a car-share program on days where the daily VMT exceeds the range capability of the car. This is selected over the low cost approach (representative of a multi-car household with an additional CV available for long trips) to better represent likely candidates for a fast charge service plan—those without an additional means of convenient, long-range transportation available.

We compare the TCO of the DO-BEV to that of the DO-CV with the aforementioned conditions for all 398 drive patterns in Figure 3. Under the low battery cost scenario, 54% of simulated drive patterns achieve a DO-BEV TCO within 20% of that of a DO-CV, while the remaining 46% of simulated drive patterns incur a TCO premium of 20% or greater when electing to drive a DO-BEV rather than a DO-CV. With the medium and high battery costs, a much larger percentage of simulated drive patterns incur a TCO premium of 20% or more when electing the DO-BEV.

A significant factor in calculating these trends is the assumed ***high cost*** *of unachievable VMT.* Similar comparisons under a low cost of unachievable VMT show that a DO-BEV is more broadly cost-effective [1]. However, this low cost of unachievable VMT assumption is not as applicable to single-vehicle households interested in BEVs. Reducing the amount and cost of unachievable VMT is thus the motivation for investigating the fast charge SP-BEV.

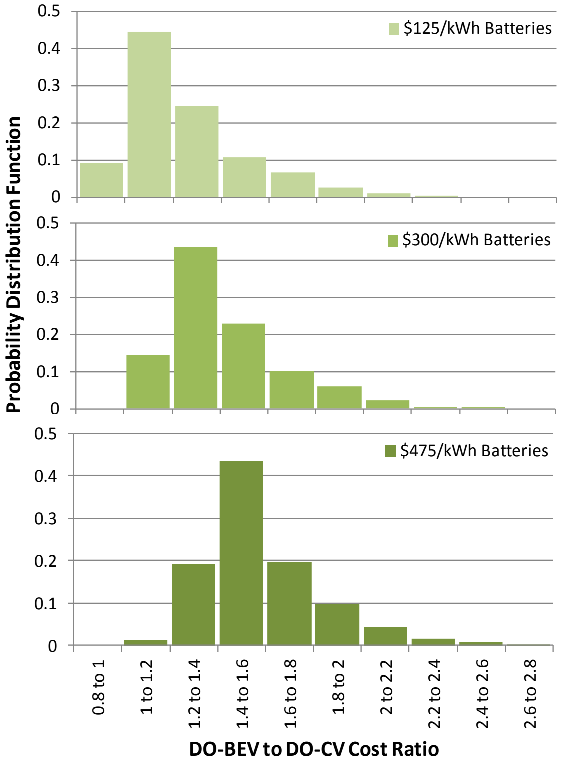

Figure 3. DO-BEV to DO-CV cost ratio distributions

4 Fast Charge Service Plan Analysis

In this section we assess the TCO to the consumer of BEVs operated under a fast charge service plan. Service plan fees are calculated using a bottom-up approach that accounts for all of the service provider's battery, infrastructure, electricity, and other costs, as well as the cost of financing such an operation. There are four phases to this analysis:

(1) Analyzing all 398 drive patterns to down-select a subset of drive patterns suitable for more detailed fast charge analysis

(2) Identifying average service usage statistics for this subset of drive patterns, including battery life, electricity usage, and fast charge frequency

(3) Calculating infrastructure requirements and service provider fees for multiple scenarios based on the identified service usage statistics and a rigorous economic model of the service provider's business

(4) Investigating individual driver economics under the calculated service provider fees.

4.1 Identifying Drive Patterns Suitable to Fast Charge Service Plan BEVs

In [3] we identified drive patterns most suitable to a BEV with a range extension service plan when the range extension features are perfect and without limit. The process down-selected drive patterns that showed the most potential for economic savings over direct ownership of either a CV or a BEV, on the basis that financial advantage over both direct ownership options is an important criterion for a consumer to consider when electing to subscribe to such a service plan. The defining characteristic of drive patterns in the resultant subset is annual mileage. The minimum annual VMT of the selected subset is 11,471 miles, and every drive pattern with an annual VMT greater than 16,446 miles from the full TCS data set is included (10% of the entire TCS data set, but 40% of the 100 selected drive patterns). This is logical given that our selected drive patterns are parsed on an economic basis, where the primary means of financial benefit is reducing the cost of gas expenditures (proportional to VMT), and the limitations of achievable mileage have been eliminated by the assumption of a perfect range extension technology. The distribution of annual VMT of this selection is shown in Figure 4.

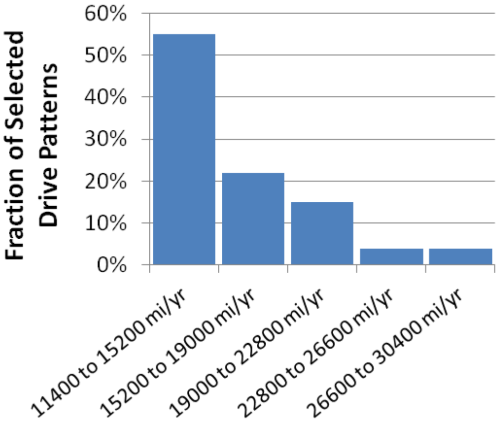

Figure 4. Annual VMT of selected drive patterns

4.2 Service Usage Statistics

Now we analyze the service usage patterns of the selected 100 drive patterns under the application of more realistic assumptions around the VMT achievable via fast charge infrastructure. Relative to both the perfect range extension and direct ownership cases, our improved set of assumptions for BEVs operated under a fast charging service plan affects three factors that must be accounted for to model service usage statistics: achievable VMT, battery degradation, and battery replacement criteria.

Achievable VMT is affected primarily by vehicle range and range extension infrastructure. We consider three vehicle ranges (50, 75, and 100 miles) and three maximum SOCs (90%, 95%, and 100%) with the vehicle properties defined in Table 1. The combination of vehicle range with time constraints to complete a day's driving and charging, as well as with the perceived inconvenience of fast charge stops, will limit daily VMT. Herein we account for the impact of time limitations by allocating a maximum of 24 hours to a day's driving and charging activities (allowing successive back-to-back occurrences of the most demanding drive days). We also restrict the number of daily fast charges to a maximum of two. When more than two fast charges would be required by a day's driving, or when the time required to complete the driving, charging, and range extensions exceeds 24 hours, we assume that the driver instead acquires a vehicle from a car-share program. Note that car-share cost accounting is performed as detailed in [1] and is not a cost covered by the service provider per our assumptions, although in practice this could be something a service provider may choose to offer with its BEV services.

Battery degradation is affected by the different cycle and SOC history induced by the utilization of fast charge infrastructure, and thus we modify our input to the battery degradation algorithm to accurately account for these effects under the fast charge service plan. However, the increased charge rate of these cycles also affects battery wear, but unfortunately the battery degradation model we employ does not internally account for additional wear mechanisms induced by high-rate charging. Although an argument might be made that the incremental wear of such high-rate charging is minimal on the grounds that (1) the time at peak charge rate of approximately 2C is limited to much less than 30 minutes due to voltage related limitations [16], and (2) early results from ongoing testing have shown no discernible effect of increased charge rate on degradation [23], we instead adjust results of the life model to exaggerate wear from fast charge cycle when desired. We do so by adding a user-defined fast charge wear factor that amplifies the impact of fast charge cycles' effect on capacity and resistance degradation. As implemented, a fast charge wear factor of 10 scales a model-predicted single-cycle capacity loss of 0.1% to 1.0% to account for the effect of increased rate. For this study we shall employ fast charge wear factors of 1 and 10 to estimate possible effects of fast charging on battery wear and to investigate the economic sensitivity thereof.

Note that home charging is unaffected: the fast charge wear factor is not applied to these charge cycles. As before we continue to assume that home charging is performed on a just-in-time schedule, such that the maximum SOC is reached just prior to the vehicle's first departure of the day.

It is also necessary to adjust the battery replacement criteria. In the direct-ownership case, we applied a cost-optimal replacement schedule. As discovered in [1], this approach results in long battery lifetimes and significantly reduced vehicle range near end of life (EOL). Although this may be financially optimal for individual drivers, higher certainty and consistency of battery performance is an attractive consumer benefit of a service plan. Further, guaranteed performance eliminates inhibitions to using fast charging infrastructure for fear of excess battery degradation. Accordingly, we enforce a battery EOL condition of 80% BOL range at 80% BOL power. Once this level of performance is breached, the service provider is assumed to replace the customer's battery with a new one to meet consumer range expectations.

The resultant average battery life, number of annual battery swaps, annual electricity consumption, and achieved utility factor are reported in Table 2 for every combination of vehicle range, max SOC, and fast charge wear factor. As might be expected, we find that the number of average annual fast charge events is reduced by increased vehicle range, promoting average battery life increases with increased vehicle range. Increasing vehicle range from 50 to 75 miles improves life due to decreased cycling. Increasing vehicle range from 75 to 100 miles, however, decreases battery life slightly due to higher average SOC through life. Similarly, max SOC has a strong effect on battery life. Finally, fast charge wear factor is shown to reduce battery lifetime noticeably for all BEV50 scenarios, due to the much increased fast charge frequency, but is seen to have little to no effect on the BEV75 and BEV100 cases.

though, implies that an alternative mode of transportation will still be necessary for some drivers on some occasions, which will impact individual driver economics.

Table 2. Calculated fast charge service plan usage statistics

Range	Max SOC	Fast Charge Wear Factor	Battery Life (yrs)	Annual Electricity (kWh)	Fast Charge Events per Year (No.)	Utility Factor
50 mi	100%	1	9.0	4952	135.1	76%
		10	7.9	4943	135.1	76%
	95%	1	11.7	5015	131.2	77%
		10	10.2	5009	128.8	77%
	90%	1	14.4	5057	126.9	77%
		10	13.0	5079	125.9	78%
75 mi	100%	1	9.8	5480	59.3	83%
		10	9.8	5479	59.3	83%
	95%	1	13.0	5519	58.0	83%
		10	12.9	5520	58.0	83%
	90%	1	14.7	5570	53.0	83%
		10	14.7	5570	53.0	83%
100 mi	100%	1	9.0	5827	29.4	86%
		10	9.0	5827	29.4	86%
	95%	1	12.1	5898	28.7	86%
		10	12.1	5898	28.7	86%
	90%	1	14.5	5954	26.8	86%
		10	14.5	5954	26.8	86%

Table 2 also shows the utility factor for each scenario, *defined as the ratio of miles travelled electrically in a BEV to the total VMT of the original drive pattern.* Recall that we impose a maximum of two fast charges per day, which reduces the frequency at which the BEV is utilized. Further, the time required for driving and charging also affects BEV utilization. For the cases studied herein, we find that vehicle range is the primary determinant of the utility factor, yielding 77%, 83%, and 86% utility factors for the 50, 75, and 100 mile BEVs. For comparison, the same high mileage drive cycles averaged a 51% utility factor in the DO-BEV case without fast charge. Clearly, all service plan cases are capable of significantly increasing utility factors. The fact that these values are not closer to 100%,

4.3 Service Provider Fee

Now we apply the usage statistics for likely subscribers acquired in Section 4.2 to calculate expected monthly service provider fees under various scenarios. To do so, we construct a financial model of a service provider that includes all capital and recurring costs, return on equity (ROE), cost of debt, and other factors as described herein, then calculate the monthly fee charged to customers that achieves ROE requirements at the end of 15 years of operation.

4.3.1 Financial Accounting

The business of the service provider is very capital intensive due primarily to the capital cost of battery packs and charging infrastructure. Thus, the means of financing the business is expected to have a considerable impact on the required service provider fee. In this analysis, we assume that the service provider acquires the necessary capital to finance the battery and infrastructure purchases of the first year of operation equally from debt and equity investments at the beginning of that year. The cost of these expenditures is determined as discussed below assuming an initial customer base of 10,000 subscribers. The cost of debt is varied from 4% to 12%, with annual debt payments calculated to pay off the full balance in 15 years where interest accrues annually. Our assumed ROE, ranging from 5% to 15%, is coupled to the cost of debt, and is applied as shall be discussed subsequently.

Annual revenue is calculated from the monthly service provider fee and the number of customers. From this the gross taxable income is computed after deducting annual operating expenses (described below), interest payments on debt, depreciation of charging infrastructure (5%/yr) and batteries (annualized per the calculated average battery life of Table 2), and any applicable loss carry forwards from previous years. Taxes are then computed against the gross taxable income assuming an average 39.3% corporate tax rate [17].

The remaining working capital at the end of each year is calculated by subtracting the annual debt payment, equity payment, operating expenses, and taxes from the annual revenue. We assume this remaining capital is spent in the subsequent year to buy batteries and build infrastructure to support additional customers. As such, the profit from year one determines the increase in customers in year two, and so on.

The monthly service fee charged is determined by an iterative process to ensure that the company net worth at year 15 is equal to the value of the initial equity investment after 15 years of growth at the prescribed ROE. For example, if the required battery and infrastructure expenses for year one totals $2M and a 15% ROE is specified, our requirement would demand that the monthly service fee be set to result in a business with a net worth of $8.14M at the end of year 15—equivalent to the value of the initial equity investment ($1M, 50% of the total year-one capital requirements) growing at 15% per year for 15 years. The net worth of the company at year 15 is defined simply as the sum of all past capital expenditures, minus the sum of all past depreciation taken, plus the profit made in the final year (note that the debt term aligns with the analysis term, and thus the company has no debt remaining at year 15 to consider).

4.3.2 Charging and Range Extension Infrastructure

The total cost of home charging infrastructure is computed from the number of new subscribers each year and a flat fee of $1,200 per charge point installed.

To compute the total cost of fast charge infrastructure, we begin by computing the fast charger utilization rate: the average hours per day a fast charge station is occupied by a customer. On the basis that a service plan customer might expect the same level of convenience and availability provided by today's network of gasoline pumps, we first calculate today's utilization rate for the average gas pump. Our calculations indicate that the average gas pump is occupied approximately 1.23 hours per day [3]. Herein we shall employ an equivalent minimum fast charger utilization rate to represent a level of infrastructure availability on par with that of the average gas pump, and one of 6.25 hours per day (five times the occupation of an average gas pump) to represent a less infrastructure intensive alternative.

From here we can compute the ratio of customers per fast charger by dividing the utilization rate by the average time per day each customer spends at a fast charger. The average fast charge time per day per customer is calculated by multiplying the average number of annual fast charges per subscriber (Table 2) by the time required per event (30 minutes for a fast charge and 2 minutes for related activities; note that waiting to use the fast charger, if required, is not included) and dividing by 365 days per year. We find this ratio varies from a low of 6 vehicles per fast charger for the BEV50 with a utilization rate of 1.23 hours per day, to a high of 153 vehicles per fast charger for the BEV100 with a utilization rate of 6.25 hours per day. Finally, dividing the number of subscribers by the ratio of customers per fast charger yields the total number of fast chargers required.

The fast charger equipment cost is determined by the power of the charger multiplied by a $200/kW cost coefficient taken from recent announcements of fast charger technology [18]. Charger power is calculated via Eq. 1 to ensure batteries are recharged to 80% of their available energy in a 30 minute period. A multiplicative factor of 1.5 is included to approximately account for the variable rate nature of li-ion battery charging induced by voltage limitations. A flat fee ranging from $5,000 to $50,000 to account for a broad range of installation costs is also included. For the range of vehicles we consider, this approach results in fast charge stations ranging from 39.8 kW and $12,968 for the BEV50 with 100% max SOC and a flat fee of $5,000, to 84.6 kW and $67,280 for the BEV100 with 90% max SOC and a flat fee of $50,000.

$$\text{Charge Power (kW)} = 1.5 \cdot 0.8 \cdot \text{Battery Available Energy (kWh)} / 0.5\ \text{h} \quad (1)$$

The total annual expenditure on fast chargers then becomes the incremental number of positions required in a given year times the individual position cost.

It is important to remember throughout the remainder of this paper that total fast charge infrastructure costs are a function of the number of customers, the fast charge utilization rate, fast charge flat fee, and battery available energy (as the charge power, and thereby power electronics cost, scale with available energy to keep fast charge time to 30 minutes).

4.3.3 Battery Expenditures

The number of batteries purchased in a given year is equal to the number of new customers plus the number of batteries required to replace those removed from service due to wear. Batteries are removed from service based on the average battery lifetime per Table 2 and the history of new customers.

The manufacturing cost of each battery is computed using the size of the battery for the specific range and max SOC combination as reported in Table 1 and one of the three aforementioned battery costs. A manufacturing-to-retail mark-up factor of 1.5 [12-14] and a sales tax rate of 6.2% are included to calculate the cost of each battery to the service provider. We then compute the total annual battery expenditure from the number of batteries purchased and the cost of each battery.

We credit the battery's salvage value at the end of its automotive life. Salvage value is computed assuming it will see service in a second use application per the methods described in [19-20], assuming $18/kWh for repurposing, a used product discount factor of 0.75, and a health factor of 0.67 or 0. The value of 0.67 is based on our calculations of second use battery life for the 80% range at EOL requirement per the methods and assumed duty cycles of [20]. Employing a value of 0 for the health factor effectively eliminates battery second use value from consideration.

4.3.4 Operating Expenses

The main operating expense considered for the service provider is electricity. The price of commercial electricity per kWh shown in Figure 5 is taken from [7] and multiplied by the amount of consumed electricity per subscriber (Table 2) and the amount of subscribers per year to yield the bulk cost of electricity to the service provider. Note that annual electricity numbers include an assumed efficiency of 85% for at-home charge points and 75% for the batteries charged on the higher-rate range extension infrastructure equipment. A fee of $20/kW/month is applied to the peak battery charging load at each range extension position to represent demand charges similar to those of Southern California Edison's TOU-GS-3-SOP [21] and San Diego Gas and Electric's AL-TOU [22] rate schedules. *Total demand charges thereby varying from $637 to $1,536 per month per fast charger are added to the bulk cost of electricity.*

We also include annual operating costs of $2,500 for each fast charge station to cover general maintenance. Finally, we include the cost of general and administrative activities at the cost of $100 per subscriber per year.

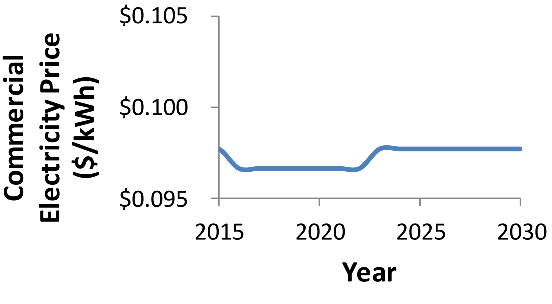

Figure 5. Employed commercial electricity prices (2012 dollars)

4.3.5 Service Plan Fee Results: Sensitivity to Variables

We calculate the monthly service provider fee for an expansive set of ROE, cost of debt, maximum SOC, vehicle range, battery manufacturing cost, fast charge wear factors, second use health factors, fast charger utilization rate, and fast charger flat fee values as discussed above, resulting in thousands of unique scenarios to evaluate. To assess the impact of an individual variable, we perform a sensitivity analysis of the monthly service fee for each variable. For each variable, we calculate the median service fee of all cases where the variable of interest is at best-case (encouraging lower service provider fees) and worst-case (encouraging higher service provider fees) values, then rank the importance of that variable based on the difference in the two calculated median service fees (see Figure 6).

For example, to study the sensitivity of battery cost, we first calculate the median of all service fees where the battery cost is set to $125/kWh (yielding a median service fee of $207/month). We repeat this process when battery cost is set to $475/kWh (yielding a median service fee of $416/month). The large difference in median service fees ($209/month) indicates the high level of impact that battery cost has on service fee; indeed, in Figure 6 we see that battery cost is the most sensitive variable in this analysis.

It is clear that across the range of variables considered in this analysis, the cost of batteries, the cost of financing, and the fast charger utilization rate (which strongly impacts the total cost of infrastructure) are the most predominant factors driving the service fee value. At the opposite end of the spectrum, we find that the maximum SOC, the fast charger flat fee, and the fast charge wear factor have negligible impact on the service fee, the latter due to the low frequency of fast charge events for most drivers.

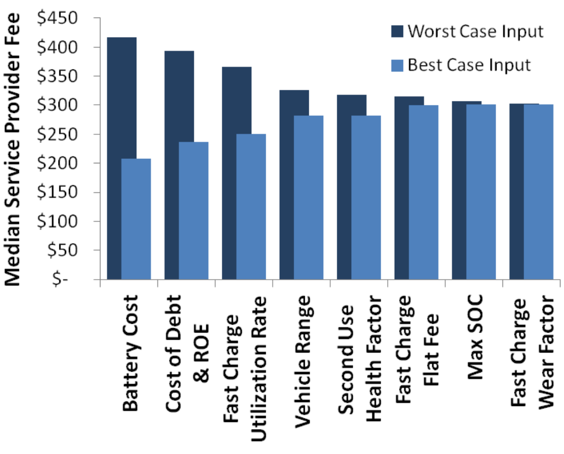

Figure 6. Sensitivity of service provider fee to variables

4.3.6 Service Provider Fee Results: Cost Breakdown

Before digging deeper into the service provider cost results, we limit our investigation to a subset of variables. First, we eliminate from consideration multiple maximum SOCs and fast charge wear factors due to their small impact, proceeding only with a maximum SOC of 90% and a wear factor of 10x to compose a conservative fast charging scenario. Second, we eliminate consideration of battery second use, as it also has a small impact and comes with considerable uncertainty. Third, we group the variables related to range extension into two classes:

(1) A high service, high cost class where the utilization rate is set to the minimum and the flat fee is set to the maximum

(2) A low service, low cost class where the utilization rate is set to a maximum and the flat fee is set to a minimum.

Finally, we restrict the cost of financing to the medium case (8% cost of debt and 10% return on equity) on the basis that the low values are unlikely without government participation and that the high values are unlikely to support a compelling business case relevant to mass markets. The cost of batteries, the vehicle range, and the range extension class are thus our remaining variables of study. The breakdown of the monthly service fee for these remaining cases is shown in Figure 7.

Three clearly evident points arise from these results. First, the service provider fees for the fast charge and battery swapping service plan (as analyzed in [3]) are not considerably dissimilar. Second, there is a strong difference in service fees between the two service plan classes. Clearly, the quantity and cost of infrastructure deployed—and thereby the level of service to the subscriber—is an important driver of service fee. Finally, we see that when battery costs are low and infrastructure cost is high, the cost of infrastructure is the largest contributor to the service fee. Thus higher vehicle range promotes lower service fees in such scenarios. In most remaining cases, though, the service fee is dominated by battery costs, and thus the service fee increases with vehicle range.

4.4 Individual Driver Economics

As noted previously, our initial assessment of individual driver economics (Section 4.1) assumed perfect range extension technology. However, truly perfect range extension is not achievable under our fast charging assumptions (Section 4.2). Thus, in this section we revisit the individual driver economics of likely subscribers using our assumed fast charge limitations and calculated service fees (Section 4.3) for 100 down-selected drive patterns (Section 4.1).

We present the results of our final TCO calculations in Figures 8 and 9. Figure 8 shows the frequency at which electing the fast charge service plan is more cost-effective than the DO-BEV. It includes all three vehicle ranges and battery prices and both the low cost, low service and high cost, high service plan classes, illustrating that the fast charge service plan BEVs can be more economical than the DO-BEV for many drive patterns under a broad spectrum of conditions. However, Figure 9 shows that electing the service plan is more cost-effective than both the DO-BEVand DO-CV options only when both the costs of batteries and infrastructure are low.

5 Conclusions

In this study we have analyzed the economics of single-vehicle household (where the cost of unachievable travel is high) BEVs operated under a service plan where fast charging is provided to extend vehicle range. Our evaluation process followed four steps: (1) identifying drive patterns best suited to a fast charge service plan, (2) modelling service usage statistics for the selected drive patterns, (3) calculating the cost of different service plan options given these statistics, and (4)

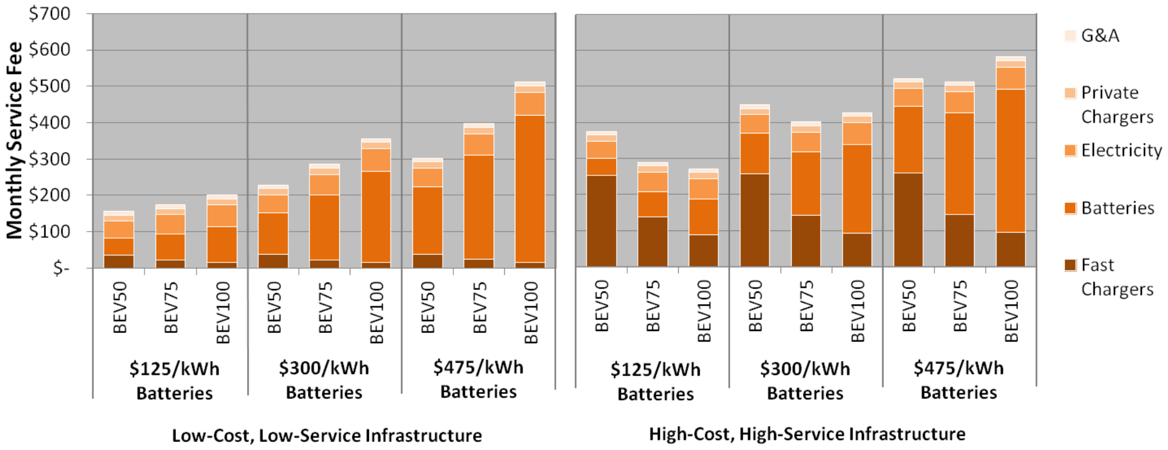

Figure 7. Fast charge service fee breakdown

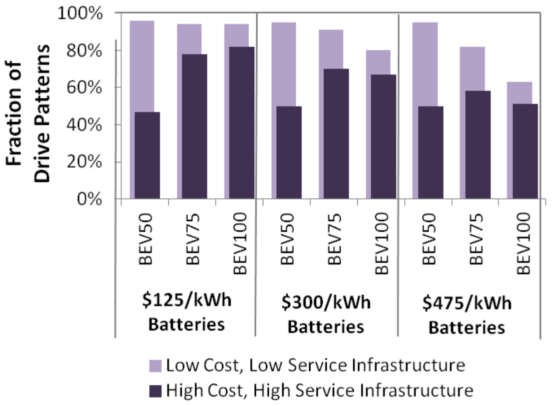

Figure 8. Frequency at which operating a BEV under a fast charge service plan is more cost effective than direct ownership of a BEV75

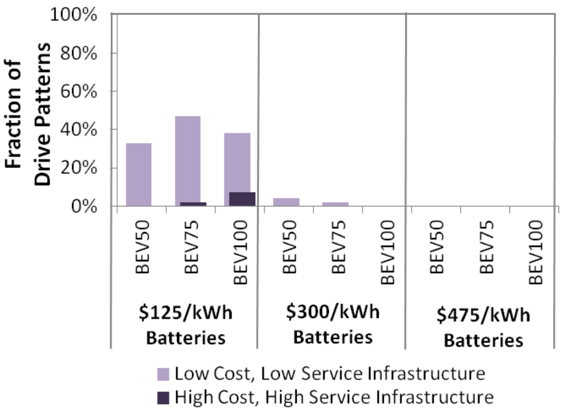

Figure 9. Frequency at which operating a BEV under a fast charge service plan is more cost effective than direct ownership of either a BEV75 or a CV

evaluating the economics of individual drivers under realistically priced service plans. For comparison, we have also calculated the TCO of both a BEV and a CV operated under a conventional direct ownership scenario. A high fidelity battery degradation model has been employed throughout to forecast battery wear, its effect on vehicle range, and required battery replacements. Real world drive patterns from the TCS project have been utilized to support the calculation of realistic battery usage, the frequency of battery swapping events, and the fraction of achievable VMT. The cost of unachievable VMT has been accounted for based on the cost of popular car share programs, making our results most generally applicable to drivers without access to an alternative lower cost, range-unlimited mode of transportation (e.g., a second non-BEV car owned by or freely available to said driver). Further, a detailed accounting of the economics of a fast charge service provider, including consideration of the amount of required infrastructure, financing of capital expenditures, recurring costs, taxes, depreciation, and required ROE has been applied to calculate the fee charged to the consumer for the service plans.

As should be expected, we find that drive patterns with high annual VMT are generally best suited to fast charge service plans. The frequency at which subscribers used fast charge infrastructure varies considerably—primarily as a function of the range of the BEV, where shorter BEV ranges encourage a higher frequency of fast charge events. For all vehicle ranges, though, the utility factor is high, spanning 76% at 50 miles to 86% at 100 miles when up to two fast charge events per day are allowed.

In calculating the monthly service fee, we find that the costs of batteries and fast charge infrastructure are the major drivers (as opposed to electricity, home charge points, and other general and administrative costs). The combination of low battery cost, reduced vehicle range, and high swapping infrastructure costs can, however, elevate the cost of fast charge infrastructure over that of batteries themselves. It should further be noted that the high level of capital expenditures involved in the service provider's business model also makes the cost of financing a very powerful variable.

In applying the calculated service fee to individual driver economics where the cost of unachievable VMT is high, our simulations show that fast charge service plans can be a more cost-effective approach to electrifying travel for a significant number of drive patterns than direct ownership of a BEV75 under a broad range of scenarios for the costs of batteries and infrastructure. However, under our assumed cost of gasoline, tax structure, and absence of purchase incentives, we find that the TCO of the BEV service plan option is rarely more cost-effective than direct ownership of a CV. Only when battery costs reach the DOE's most aggressive target ($125/kWh) and infrastructure costs achieve our lowest assumed values do we see significant numbers of drive patterns benefiting economically over the CV option.

It should be noted that these results do not quantify the full potential of a service provider to improve the relative value of BEVs. Indeed, the economics of a service provider are yet to be fully optimized. For example, multi-tiered fee and service strategies, optimal allocation and down-cycling of aged batteries, revenue generation via aggregated vehicle-to-grid services, and other avenues that could further improve individual driver economics are yet to be explored. Moreover, it may be necessary to perform a detailed study of the geographic and temporal distribution of range extension events, which could significantly affect the total cost of infrastructure and subscribers' utility factors.

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References

[1] Neubauer, J., Wood, E., Brooker, A., "Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies," Journal of Power Sources 209 (2012) 269-277.

[2] Neubauer, J., Wood, E., Brooker, A., "Sensitivity of plug-in hybrid electric vehicle economics to drive patterns, electric range, energy management, and charge strategies," Journal of Power Sources 236 (2013) 257-364.

[3] Neubauer, J., Pesaran, A., "A Techno-Economic Analysis of BEV Service Providers Offering Battery Swapping Services," SAE Technical Paper 2013-01-0500, 2013, doi:10.4271/2013-01-0500.

[4] Traffic Choices Study – Summary Report, Puget Sound Regional Council, April 2008.

[5] http://www.gpo.gov/fdsys/pkg/FR-2011-07-06/html/2011-14291.htm [Accessed: Sept 22, 2011].

[6] Lohse-Busch, H., Small EV Testing and Analysis, Presentation to DOE. Argonne National Laboratory November 17, 2009.

[7] Annual Energy Outlook 2011 With Projections to 2035, U.S. Energy Information Administration, DOE/EIA-0383(2011), April 2011.

[8] Howell, D., "Annual Merit Review: Energy Storage R&D and ARRA Overview," March 2011, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2010/electrochemical_storage/es00a_howell_2010_o.pdf [Accessed: June 5, 2012].

[9] Dinger, A.; Martin, R.; Mosquet, X.; Rabi, M.; Rizoulis, D.; Russo, M.; Sticher, G. Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020; Boston Consulting Group: 2010. http://www.bcg.com/documents/file36615.pdf

[10] Hensley, R.; Knupfer, S.; Pinner, D. Electrifying cars: How three industries will evolve; McKinsey & Company: 2009.

[11] Lache, R.; Galves, D.; Nolan, P. Vehicle Electrification: More rapid growth; steeper price declines for batteries; Deutsche Bank: 2010.

[12] Rogozhin, A., Galaher, M., Helfand, G., McManus, W., "Using indirect cost multipliers to estimate the total cost of adding new technology in the automobile industry," Int. J. Production Economics, Vol. 124, issue 2, April 2010, pg. 360-368.

[13] Vyas, A., Santini, D., Cuenca, R., April 2000. Comparison of indirect cost multipliers for manufacturing. Argonne, IL: Center for Transportation Research, Energy Systems Division, Argonne National Laboratory.

[14] Sierra Research, Inc., November 21, 2007. Study of industry-average mark-up factors used to estimate changes in retail price equivalent (RPE) for automotive fuel economy and emissions control systems. Sierra Research, Inc., Sacramento, CA.

[15] Smith, K.; Earleywine, M.; Wood, E., Neubauer, J.; Pesaran, A.; "Comparison of Plug-In Hybrid Electric Vehicle battery Life Across Geographies and Drive Cycles," SAE Technical Paper 2012-01-0666, 2012, doi: 10.4271/2012-01-0666.

[16] Simpson, M.; Markel, T.; "Plug-in Electric Vehicle Fast Charge Station Operational Analysis with Integrated Renewables," Electric Vehicle Symposium 26, 2012

[17] http://taxfoundation.org/article/national-and-state-corporate-income-tax-rates-us-states-and-oecd-countries-2011 [Accessed: June 5, 2012].

[18] http://www.greencarreports.com/news/1068509_nissan-leaf-mitsubishi-i-rapid-charging-gets-cheaper-thanks-to-nissan [Accessed: June 5, 2012]

[19] Neubauer, J.; Pesaran, A. "The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications." Journal of Power Sources 2011, 196, (23), 10351-10358.

[20] Neubauer, J, Pesaran, A., Williams, B., Ferry, M., Eyer, J., "A techno-economic analysis of PEV battery second use: repurposed-battery selling price and commercial and industrial end-user value," SAE Technical Paper 2012-01-0349, 2012, doi:10.4271/2012-01-0349.

[21] "Schedule TOU-GS-3-SOP Time-of-Use - General Service - Super Off-Peak - Demand Metered." Southern California Edison. http://www.sce.com/NR/sc3/tm2/pdf/ce282.pdf [Accessed: June 5, 2012].

[22] "Customer Rate Information Schedule AL-TOU Secondary," San Diego Gas & Electric. http://www2.sdge.com/tariff/com-elec/ALTOUSecondary.pdf [Accessed: June 5, 2012].

[23] Francfor, James; Shirk, Matthew; "DC Fast Charge Impacts on Battery Life and Vehicle Performance," DOE Vehicle Technologies Office Annual Merit Review, Washington DC, May 2013.

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