Exploring Electric Vehicle Battery Charging Efficiency

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The National Center for Sustainable Transportation Undergraduate Fellowship Report

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September 2018

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Introduction

Plug-in Electric Vehicles (PEVs) encompass both Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs). PEVs are more environmentally friendly, economical, and efficient than Internal Combustion Engine Vehicles (ICEVs). ICEVs are about 35 to 45% efficient, versus PEVs, which are about 75 to 85% efficient. With the massive influx of PEVs entering the market, it is critical to optimize the electricity used for charging these vehicles to reduce CO₂ emissions and costs to the consumer. A pivotal way to optimize electricity is to improve PEVs’ charging efficiencies. This paper seeks to further optimize battery charging efficiency and electric vehicle policy by studying specific factors - level of charging, temperature, state of charge, and charging power - that affect battery charging efficiency itself.

Background

Numerous factors affect electric vehicle battery charging efficiency, defined as the percentage of power drawn from the electric grid that is retained by the vehicle battery (1).

Factors

The factors that affect battery charging efficiency studied in this paper are the level of charging, state of charge, temperature, and charging power. Other factors not included in this study are duration, battery capacity, and battery life.

Level of Charging

The two most common types of charging are Level 1 (120 Volt) and Level 2 (240 Volt) charging. Level 1 charging, the typical at-home wall charger, can charge 100 miles of range in 24 hours, versus level 2 charging, which can charge 100 miles of range in two to ten hours (2). According to a past study conducted by the Vermont Energy Investment Corporation, level 1 charging was on average 83.8% efficient, versus level 2 charging which was on average 89.4% efficient (1).

Temperature

The temperature of the battery itself effects the battery charging efficiency of the vehicle. The battery temperature is determined by the ambient temperature. Studies have found that cold temperatures can lower range of electric vehicles as much as 25% (3). On the other hand, hot temperatures can increase efficiency by extremely small margins (3). However, it may also degrade the battery faster, although battery life is not focused on in this study (4).

State of Charge

State of Charge (SOC) is defined as the remaining capacity of a battery (5). Many charging events conclude with the car done charging, in other words, having an end state of charge of 100%. In many cases, more results can be discovered by analyzing starting state of charge. A common pattern found by analyzing state of charge is that the vehicle will begin to charge at a much slower rate, taking in less electricity.
**Charging Power**

Charging power is defined as total energy received by the battery divided by the duration of the charging event. Charging power is measured in kilowatts (kW). The charging efficiencies of cars were overall lower by about 4% when the charging power was less than 4 kW (1).

**Methodology**

This study utilized data from the Plug-in Hybrid & Electric Vehicle Research Center’s eVMT Project to analyze the battery charging efficiency of cars. Fleetcarma loggers were installed in four different vehicles included in Table 1.

**Table 1. Fleetcarma Vehicle Data**

<table>
<thead>
<tr>
<th>Make, Model</th>
<th>Tesla, Model S</th>
<th>Kia Soul EV</th>
<th>Audi A3 e-tron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2012-2018</td>
<td>2015</td>
<td>2016</td>
</tr>
<tr>
<td>Number of</td>
<td>1685</td>
<td>74</td>
<td>211</td>
</tr>
<tr>
<td>Charging Events</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The loggers provide data for each charging event per car including:

- Start Date and Start Time;
- Duration;
- Charging Level;
- Charger Energy (kWh);
- Charger Loss (kWh);
- Starting and Ending State of Charge (%);
- Location.

Efficiency and Charging Power were then calculated from the provided data. Efficiency was calculated using charger energy divided by charger loss. Power was calculated by dividing charger energy by duration. Data was then analyzed using the statistical program JMP.

**Limitations**

The data included in this paper are all from another study. While sufficient data is provided to see results, the data is limited by some factors:

1. The vehicles in the eVMT study were chosen for different reasons than those of this study. As a result, this study analyzes only four vehicles.
2. Because the participants use their vehicles freely, charging events vary in most variables. As a result, all the factors discussed are variable and uncontrolled.
Because of these limitations, the Kia Soul EV did not have enough data to find significant results. The Tesla Model S has the clearest results, and the Audi A3 e-tron follows with similar results in most cases.

**Results**

The aforementioned factors were all compared and analyzed with efficiency. The results are shown and explained below.

**Level of Charging and The Density Graph of Efficiency**

To illustrate the difference in efficiency between level 1 and level 2 charging, a density graph was made (see Figure 1). The level 1 charging curve contains 49 points of data, versus the level 2 charging curve that contains 1636 points of data. Furthermore, the mean of the level 1 charging curve is 0.694 compared to the level 2 charging curve which is 0.869. The level 1 charging curve has two peaks, one at around the mean of level 2 charging, and a slight peak at around .2. The difference in means and the fact that the level 1 charging curve has two peaks signals that level 2 charging is more efficient. This point supports previous research. Additionally, the level 2 charging curve mean is similar to means of level 2 charging found in previous research. The level 1 charging curve mean may need more data to support previous findings.

![Figure 1. Density Graph of Tesla Model S Efficiency](image)
**Start Time vs. Efficiency**

For this study, start time was used as a factor to indicate temperature change. Because temperature changes throughout the day, start time at some points is indicative of variable temperature. Below is a scatterplot of start time versus efficiency (see Figure 2).

![Efficiency vs. Start Time](image)

**Figure 2. Scatterplot of Tesla Model S Start Time vs. Efficiency**

The graph illustrates little to no relationship of start time to efficiency. The fit line is tilted downward, but would barely signal a relationship, as the majority of points are at about .87 efficiency. Because this study has been conducted over the course of the summer, most charging events will be taken at warm temperatures, not extremely cold ones. As a result, this data is consistent with the finding that warm temperatures have marginal effects on efficiency.

**Starting State of Charge vs. Efficiency**

Similar results were found when comparing the Tesla Model S (see Figure 3) and Audi A3 e-tron (see Figure 4). Note that the y-axis for the Audi A3 e-tron is different, and its efficiency ranges from 0.82 to 0.94 rather than 0 to 1.

Both vehicles, the Tesla Model S especially, exhibit signs of “trickle charging.” The fit curve of the Tesla Model S graphs dips towards 90% efficiency because of the substantial amount of points towards the latter ends of efficiency. The Audi A3 e-tron graph seems to demonstrate similar results as the Tesla Model S. Because it has less points, the efficiency is less consistent across the x-axis. However, at the higher ends of starting state of charge, the efficiency seems to drop. If the Audi A3 e-tron graph contained more data points, it would most likely indicate a trend similar to the graph of the Tesla Model S.
Figure 3. Scatterplot of Tesla Model S Starting State of Charge vs. Efficiency

Figure 4. Scatterplot of Audi A3 e-tron Starting State of Charge vs. Efficiency
**Charging Power vs. Efficiency**

A final outcome of the study is the mapping of efficiency with charging power. The graph of the Tesla data illustrates a varying efficiency at the beginning, and as power increases efficiency seems to remain constant (see figure 4). The Audi A3 e-tron graph seems to depict an incomplete portion of a graph. Note the axis are different, the x-axis ranging from 0.046 to 0.058 whereas the Tesla graph’s x-axis ranges from 0 to .2. The y-axis is also different, again ranging from .82 to .94 compared to 0 to 1.

Low amounts of charging power are indicative that the car is either almost done charging or plugged in and unplugged quickly. After about .6 kW, efficiency is constant with few exceptions, signaling that efficiency is constant if a certain amount of kW is inputted. The Audi A3 e-tron graph is a small part of the Tesla graph. If there were instances of low power, it might indicate that efficiency is lower.

![Figure 4. Scatterplot of Tesla Model S Charging Power vs. Efficiency](image-url)
Discussion

This study has, with all factors, supported the findings of previous studies. While battery charging efficiency is usually about 85% it should be noted that at high state of charge trickle charging continues to occur. Therefore, it should be recommended to electric vehicle consumers to charge at a starting state of charge less than 90%. By doing so, a consumer can be more efficient charging, and more economical. It can also be recommended to charge at level 2 charging rather than level 1 charging when possible.

Potential for Further Study

While this study has supported all findings of previous studies, it could be furthered with more scrutiny and detail. The Tesla Model S data supported previous studies, but the amount of data for other vehicles such as the Kia Soul EV, and Audi A3 e-tron was insufficient to make similar, complete conclusions for each individual vehicle. In addition, other factors contribute to electric vehicle battery charging efficiency. More studies could be conducted on factors such as battery age, duration, battery life, and type of battery.
References


5. Savandkar, A., Watvisave, D. S. Study of Thermal and Electrochemical Characteristics of Li-ion Battery. 2015.