Electric Vehicle Charging Efficiency in Extremely High Temperatures

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Introduction

Plug-in electric vehicles (PEVs) are more efficient and less polluting than internal combustion engine vehicles (ICEVs). ICEVs have efficiencies around 35 to 45%, whereas PEVs can run between 85-95% charging efficiency [1]. Charging efficiency is defined as the percentage of power drawn from the electric grid that is taken up by the vehicle battery. 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. Several critical factors that affect electric vehicle charging efficiency are the type of charging, temperature, and State of Charge (SOC).

The two most common types of charging are Level 1 (120 Volt) and Level 2 (240 Volt) charging. Level 1 has a much slower charging rate, being able to charge an electric battery of 100 miles of range in about 24 hours, whereas Level 2 charging can supply this energy in 4-12 hours. Studies have shown that for charging events <4kWh, Level 1 and Level 2 have charging efficiencies of 74.2% and 87.2%, respectively. Charging efficiency is also largely dependent on the ambient temperature during charging. For temperatures below 50 °F and above 70 °F, Level 2 was 7.6% and 8.5% more efficient than Level 1, respectively [2]. It should be noted that charging temperature affects the battery life cycle, however that is not the focus of this study. The amount of electricity used for charging also plays a role in charging efficiency. Charging quantities of less than 4 kWh were found to be generally less efficient than those larger than 4 kWh, with the inefficiency being much more significant in Level 1 charging. Finally, the State of Charge, or the remaining capacity of a battery, affects the overall charge efficiency of PEVs. The SOC is commonly compared to the fuel gage of a conventional internal combustion engine and measured as a percentage of how charged the battery is. With these four factors significantly affecting charging efficiency, a review of studies analyzing the extent of their effect was conducted [3].

Background

The following discusses the research done prior to creating the methodology of this study, as well as this study’s purpose.

Literature Review

A wide variety of experiments have investigated the effects of temperature on charging efficiency. The table below includes a literature review of similar studies that analyzed the effects on charging level and temperature on charging efficiency.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Methods</th>
<th>Vehicle Type</th>
<th>Region</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho National Laboratory [1]</td>
<td>2013</td>
<td>EVSE Data</td>
<td>PEVs</td>
<td>Idaho, USA</td>
<td>For Level 2 charging, Higher temperatures result in marginally faster and marginally longer charging.</td>
</tr>
<tr>
<td>Lindgren, &amp; Lund [4]</td>
<td>2018</td>
<td>Matlab-based Simulation</td>
<td>PEVs</td>
<td>Finland</td>
<td>At temperatures &gt;104 °F, performance is generally unaffected but degradation and self-discharge are higher. Efficiency was maximized near 68 °F. Cabin preconditioning can improve fleet efficiency.</td>
</tr>
<tr>
<td>Qujan et al. [6]</td>
<td>2010</td>
<td>Simulation with Chinese program</td>
<td>GM E1, Nissan Altra, Toyota RAV 4</td>
<td>Southern China</td>
<td>An increase in ambient temperatures drastically reduces EV battery life. Li-ion batteries have a longer lifetime and lower sensitivity to ambient temperature than lead-acid and NiMH batteries.</td>
</tr>
<tr>
<td>Rugh et al. [7]</td>
<td>2011</td>
<td>PEVs</td>
<td></td>
<td></td>
<td>High temperature decreases longevity of batteries, and low temperature decreases immediate performance of batteries. Optimal range for overall battery performance is 15°-35°C.</td>
</tr>
<tr>
<td>Sears et al. [8]</td>
<td>2014</td>
<td>Modeling</td>
<td>Chevy Volt, Nissan Leaf</td>
<td>Vermont, USA</td>
<td>On average, Level 2 charging was 5.6% more efficient than Level 1 (89.4% vs. 83.8%). Efficiency gains of Level 2 charging also increased under low (&lt; 50°F) and high (&gt; 70°F) temperatures.</td>
</tr>
</tbody>
</table>

It was generally found that higher temperatures slightly decrease the duration of charging and either is insignificant or slightly increases the short-term charging efficiency. In the long term, however, increased temperatures have been found to decrease the battery capacity. Although several similar studies have been conducted, very few of them were conducted in extremely high temperatures. Of the ones that were, the methods used software simulations or modeling.
Purpose
The purpose of this study is to examine real PEVs exposed to extremely high temperatures at the workplace with the goal of providing the most realistic short-term effects on charging efficiency. Climate change threatens to increase the intensity and duration of extreme heat in the Western United States. California is one of the largest global electric vehicle markets, predicting about 1.5 million PEVs by 2025 [1]. This paper aims to better understand the relationship between extreme temperatures and charging efficiency with the goal of advising policy makers, PEV owners, and electric vehicle manufacturers.

Methodology
The data analyzed for the study was acquired through three primary methods. These three methods included monitoring battery temperature, energy output from electric chargers, and energy retention in the vehicle battery. The PEVs analyzed in the study are a 2017 Toyota Prius Prime, a 2011 Nissan Leaf, a 2012 Nissan Leaf, and a 2013 Tesla Model S.

Monitoring Temperature:
To measure charging efficiency at different temperatures, the temperature of the vehicle battery had to be monitored during charging. A Fluke IR Thermometer was used to record the battery temperature. Because different electric vehicle models have different battery locations, the specific location of each vehicle in the study had to be found. Figure 1 displays the location of the battery in a 2011 and 2012 Nissan Leaf.

Figure 1: Location of battery in 2011, 2012 Nissan Leaf.

Once the battery locations were identified, the temperature variance across charging batteries had to be acknowledged. To produce a representative temperature value for the entire battery, four locations were marked on each battery and temperature was recorded by the Fluke IR Thermometer. These values were averaged and taken each hour for every charging car in the study.

Energy Output
To find charging efficiency, both the charger output and retained energy had to be quantified. The PHEV uses Hobolink to track the energy demand of every appliance in the building, including
the 4 electric chargers used in the study. Exported Hobolink data includes the amps and volts used by each charger every minute during the study. This data was converted to kilowatt hours (kWh) and used as the energy entering the battery before AC-DC conversion.

Retained Energy

The energy retained by the battery was monitored through vehicle loggers. Loggers were installed in every vehicle in the study and used to record different parameters for each charging event, including the starting time and duration, retained kWh, and starting and ending SOC by minute. Using the data from Hobolink and vehicle loggers, the charging efficiency was calculated using the following equation.

\[
\text{Charging Efficiency} = \frac{\text{Energy Output}}{\text{Retained Energy}}
\]  

Where: Energy Output comes from Hobolink and is recorded in kWh. Retained Energy comes from vehicle loggers and is recorded in kWh.

Complications:

There were a variety of complications that had to be considered to ensure accuracy in the study. For one, our initial efficiency readings produced values over 100%, meaning that loggers were recording more energy retained in the battery than was being output. Initially, it was expected that the Hobolink multiplier used to estimate watts was incorrect. The EV chargers were analyzed with voltmeters to test accuracy in energy output, and these values were compared with both the Hobolink and vehicle logger data. After testing, the multiplier was found to be correct, and rather it was an issue with the loggers. The loggers calculate the energy lost in certain vehicle models using a set multiplier, regardless of the temperature conditions during the charge. Due to this estimation, the vehicle models that produce use this multiplier were creating the efficiency inaccuracy and had to be excluded from the study.

Additionally, loggers in specific vehicle models produced retained energy data before alternating current (AC) to direct current (DC) conversion. The electric vehicle chargers in this study, which are the standard in the field except for DC Fast Chargers, use AC current, whereas electric vehicles run on a DC battery. Electric vehicles are equipped with an AC to DC converter, which is where the majority of energy loss occurs during charging events. Because the loggers recorded energy before the conversion, efficiencies of 100% were inaccurately reported. To combat this complication, the complete battery capacity was researched and compared with the energy output. It was initially hypothesized that given the amount of energy input to the battery over a certain duration and up to a reported battery capacity, the charging efficiency could be calculated. However, the reported battery capacity is different than the true capacity both due to manufacturing alterations made to increase battery life, as well as standard battery degradation over time. As a result, vehicles experiencing the AC to AC complication had to be excluded from the study as well.
Analysis:

After approximately a month of conducting the study, the following results were obtained.

Figure 2: Efficiency vs. Temperature for Prius Prime, Nissan Leaf, and Tesla Model S (Level 2).

Figure 2 indicates a minimal effect of high temperatures between 70 and 105 °F on charging efficiency. Between this range, an average efficiency of 0.904 was found. It is important to note that the outlier below an efficiency of 0.8 is the result of trickle charging. Trickle charging occurs when the battery is nearly at a complete starting State of Charge (SOC), at which point energy enters the battery at a much slower rate and efficiency drops significantly. Data points collected during trickle charging events were not included in this data analysis.

Figure 3: Charging Speed (kW) vs. Temperature for Prius Prime, Nissan Leaf, and Tesla Model S (Level 2).
Charging speed in Figure 3 was determined by summing the total amount of energy output during a charging event in kWh and dividing it by the charging duration to obtain kW. Therefore, charging speed is equivalent to power. This figure indicates that charging speed is not significantly affected by temperatures between 70 and 105 °F. This figure does not include any trickle charging events, however trickle charging events would be represented by a much lower charging speed. Figure 3 only contains Level 2 charging events, which result in higher charging speeds with respect to Level 1. If Level 1 events were included, it is expected that lower charging speeds would be observed again regardless of temperature. Previous literature reviews found that charging speed should slightly increase with temperature, however this analysis does not produce the same conclusion.

Figure 4: Efficiency vs. Duration (hours) for Tesla Model S compared with PHEV study’s results.

Figure 4 compares the results of this study with logger data for over 500 charging events in different Tesla Model S vehicles with Level 1 and 2 charging. First, the figure indicates that the results of this study are realistic and within the realm of other charging efficiency events. The yellow dots representing this study are often slightly above the Tesla Model S efficiencies, which could be for a variety of factors including temperature, the energy loss calculation, chemical reactions specific to the vehicle model, or others. The charging events with very short durations often represent trickle charging events which result in lower efficiencies. After about a 1-hour duration, eliminating the possibility of a high starting SOC, the efficiency reaches and remains primarily between 0.8 and 0.9.
Hobolink is associated with the energy output, and Fleetcarma is associated with the energy retained in the battery. Figure 5 shows a consistent parallel between the energy output and energy retained for all temperatures included in the study. Because the retained energy follows the trend of energy output, this again indicates that the charging efficiency is relatively unchanged with respect to temperature. Power is energy per unit time; Thus, although charging events with different durations will result in different kWh outputs, dividing by duration and comparing power allows for a commensurate analysis. Figure 5 compares the maximum power in each charging event rather than the average value, which shows that a very similar maximum energy per unit time around 3.3 is reached across different temperatures and different vehicle models. This figure does not, therefore, necessitate that the overall charging efficiency is relatively equal regardless of temperatures between 70 and 105 °F. However, in comparison with Figure 2, it can be determined that both the overall efficiency and maximum power of charging events are relatively unaffected by high temperatures.

Figure 5: Max Power vs. Temperature

Figure 6: Efficiency vs. Starting SOC (Level 2)
Figure 6 analyzes the charging efficiency with respect to the starting State of Charge. The figure shows a slight increase in efficiency at higher SOC, however this result is inconsistent with the findings of other studies. After discussing the findings with Nissan representatives, it appears unrealistic that the efficiency is lower in an empty battery. The results of this comparison may be due to too few data points, which would necessitate additional recordings. Data points for this figure were recorded at the top of every hour, meaning that the second hour of a charging event would be counted as a new data point. A battery that has been charging over the past hour would be heated, potentially causing a slight increase in efficiency despite not having a true SOC around 55%. Although this figure should not be used to conclude that efficiency increases between a SOC of 0 and 55%, it can be used to approximate that 55% of a SOC is filled up within an hour of Level 2 charging.

**Conclusions:**

The results of this study indicate an insignificant relationship between high temperatures and charging efficiency. This varies from the effect of cold temperatures which drastically reduce charging efficiency in electric vehicles. Charging speed and maximum power during charging events also proved to be unaffected. It should be noted that these results are only consistent for short term effects on the battery, and do not indicate a lack of long-term degradation. It is completely possible that consistent exposure to extremely high temperatures will reduce battery capacity and charging efficiency, and this effect should be analyzed over a long-term investigation. Further, this study only investigates charging efficiency with Level 1 and Level 2 chargers. Other studies have found that Level 3 chargers, such as Tesla Superchargers, significantly degrade battery capacity. This effect may be exacerbated by extremely high temperatures and should be the focus of additional studies.
References


