

Plug-In Electric Vehicle Charge Time Robustness

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ABSTRACT

With the introduction of plug-in electric vehicles (PEVs), the conventional mindset of “fill-up time” will be challenged as customers top off their battery packs. For example, using a standard 120VAC outlet, it may take over 10hrs to achieve 40-50 miles of EV range-making range anxiety a daunting reality for EV owners. As customers adapt to this new mindset of charge time, it is critical that automotive OEMs supply the consumer with accurate charge time estimates. Charge time accuracy relies on a variety of parameters: battery pack size, power source, electric vehicle supply equipment (EVSE), on-board charging equipment, ancillary controller loads, battery temperature, and ambient temperature. Furthermore, as the charging events may take hours, the initial conditions may vary throughout a plug-in charge (PIC). The goal of this paper is to characterize charging system sensitivities and promote best practices for charge time estimations.

INTRODUCTION

PricewaterhouseCoopers (PwC) estimates that over 500 thousand EVs will be introduced to the global market by 2015 [A], creating a new realm of vehicle interfaces, entrepreneurship opportunities, and consumer demand. To date, there have been multiple research papers with a focus on the interaction between the vehicle and the utility grid-examples include vehicle-to-grid (V2G), interruptible charging, dynamic energy pricing, and time-of-use (TOU) charging [B]. Additionally, there are numerous case studies about PEV market penetration and the capacity of local utilities to provide power for the PEVs [C],[D],[E]. However, there has been little analysis directed toward the emerging idea of plug-in charge (PIC) time.

As a result, the goal of this paper is to analyze PIC time, specifically focusing on the accuracy of Level 1 (120VAC) and Level 2 (240VAC) on-board charging [E]. Customers may perceive the accuracy of charge time (CT) predictions differently based on the programmable charge modes: immediate, departure based, and rate based [G]. For example, with immediate and rate based charging, underestimates of the CT may be acceptable, but with departure based charging the customer expects-if feasible-a full charge by the selected departure time and anything otherwise is intolerable. In turn, it is important to understand not only the accuracy of CT predictions but also the sensitivity of CT estimates to guarantee a full PIC by the departure time.

To complete the CT sensitivity analysis, an energy system was defined. The energy system included a power source, parasitic loads, and an energy sink-the rechargeable energy storage system (RESS). After defining the governing system of equations, each component was seeded with a default value and a corresponding uncertainty. Next, a sensitivity analysis was performed to provide a confidence band for Level 1 and Level 2 PIC.

Although the sensitivity study utilized multiple assumptions, it is clear that Level 2 charging is much more robust to system variation than Level 1 charging. Wall power variation is the most significant noise factor, impacting charge time (CT) estimations by as much as ± 0.7 hours for Level 1 charging and ± 0.2 hours for Level 2 charging. Furthermore, the use of active thermal conditioning during a PIC has a significant impact on the fidelity of Level 1 CT estimates in extreme ambient temperatures, which primarily results from sporadic temperature fluctuations from charge-to-charge.

After completing the sensitivity study, the results, assumptions, and shortcomings of the analysis are discussed.

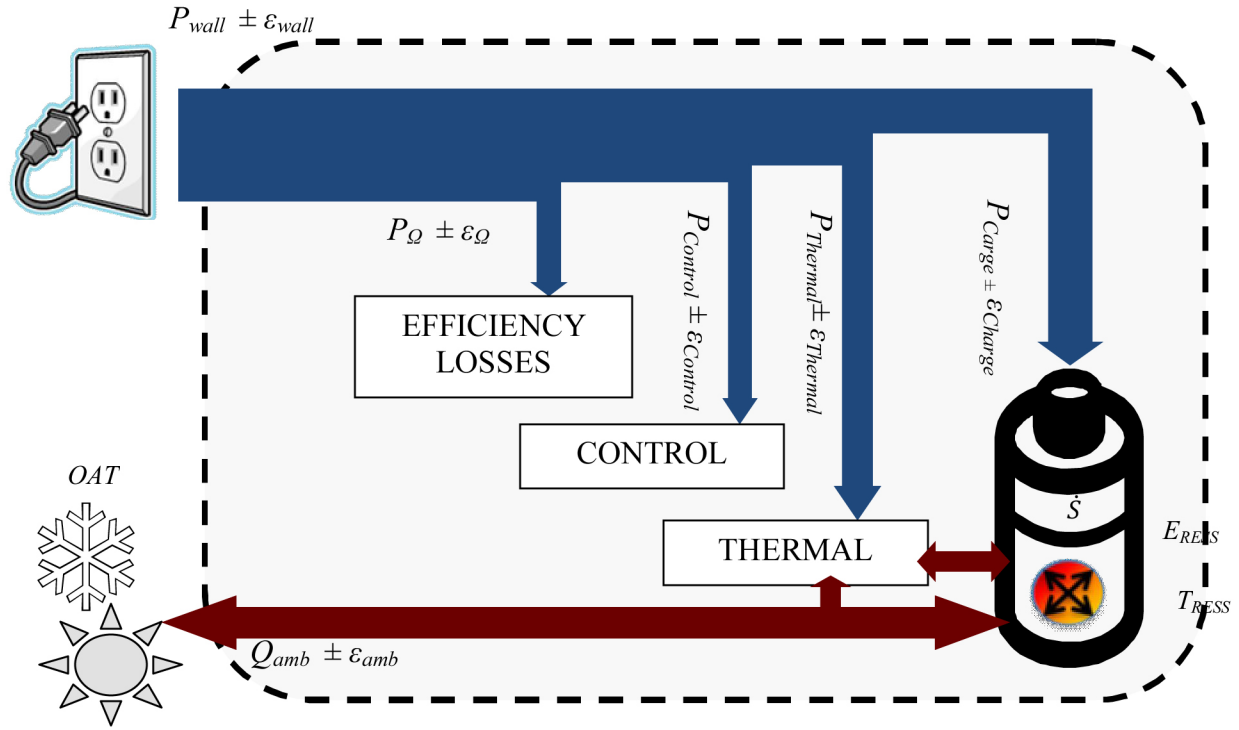


Figure 1. Bounded energy system used for estimating the PIC times.

The discussion briefly highlights control and noise factors and provides an example of an improved system. For future work, the following logic must be pursued: 1) what is considered an ‘accurate’ CT estimate (10/30/60 minutes), 2) how much does the customer value an accurate CT estimate, and 3) what value is there to the OEM to have an accurate CT estimate. Once the preceding questions are answered, one can use the sensitivity analysis to outline a cost-justifiable means to adjust the fidelity of plug-in CT estimations.

METHODS

The first step towards estimating plug-in charge times is establishing a bounded energy system; this system is displayed in [Figure 1](#).

Next, the primary factors for each component of the system should be defined ($E \rightarrow$ Energy, $P \rightarrow$ Power), where $E_{RESS,full}$ represents the energy required to fully charge the RESS (rechargeable energy storage system) and $CTtF$ represent the time required to fully charge the RESS:

$$E_{RESS,final} = E_{RESS,0} + \int_0^{CT} P_{Charge} dt \quad (1a)$$

$$E_{RESS,full} = E_{RESS,0} + \int_0^{CTtF} P_{Charge} dt \quad (1b)$$

$$P_{Charge}(t) = P_{Wall}(t) - P_{\Omega}(t) - P_{Control}(t) - P_{Thermal}(t, Q_{amb}, \dot{S}) \quad (2)$$

If the power values remain constant, then the time until fully charged, $CTtF$, can be reduced to the following elementary equation; note, in this equation the primary variation arises from the RESS energy estimates ($E_{RESS,full} - E_{RESS,0}$):

$$CTtF = \frac{E_{RESS,full} - E_{RESS,0}}{P_{Charge}} = \frac{E_{RESS,full} - E_{RESS,0}}{P_{Wall} - P_{\Omega, EVSE} - P_{\Omega, OBC} - P_{Control} - P_{Thermal}} \quad (3)$$

However, the charging system is typically constrained by the power source (P_{Wall})-especially with Level 1 charging systems-and, as a result, P_{charge} becomes a function of P_{Wall} and a number of parasitic loads (P_{Ω} , $P_{control}$, $P_{Thermal}$). In turn, a rather elementary CT estimation can quickly snowball into a multidimensional predictive algorithm. To simplify this model, this report assumes an average power consumption for each parasitic load throughout the entire charge event; these averaged power values are described below.

POWER SOURCE (P_{Wall})

Presently, there are three levels of PIC defined by SAE J1772 [E]:

1. AC Level 1: 120V AC, 12A or 16A for a minimum circuit breaker of 15A and 20A, respectively.

2. AC Level 2: 208 to 240V AC, 1-phase, less than 80A

3. DC Charging: under development

This paper will focus solely on Level 1 and Level 2 charging. For Level 1 and Level 2 PIC, the charge process is constrained by AC current limits (I_{limit}); as a result, the source power to the charging system, P_{WALL} , becomes directly proportional to the source voltage (V_{WALL}):

$$P'_{WALL} = I_{limit} V_{WALL}, \quad (4)$$

The source voltage can vary from street to street, home to home, circuit to circuit, and even based on the hour of day; these variations will be classified as $\epsilon_{wall,Noise}$. In addition to the noise variations, there is an inherent error based on the fidelity of the measurement instrumentation; this inherent error will be referred to as $\epsilon_{Wall,Measure}$. Assuming a constant current limit, I_{limit} , the equation for source power becomes:

$$P_{WALL} = I_{limit} (V_{WALL} \pm \epsilon_{Wall,Noise}) \pm \epsilon_{Wall,Measure} = P'_{WALL} \pm \epsilon_{WALL} \pm \epsilon_{Wall,Measure} \quad (5)$$

The default power values used for the sensitivity study are 1.3kW (12A * 110V) and 3.5kW (16A*220V) for Level 1 and Level 2 charging, respectively.

Additionally, the noise variation associated with the power values, ϵ_{WALL} , is assumed to be $\pm 0.1kW$ and $\pm 0.2kW$ for Level 1 and Level 2 charging, respectively; these variations were derived from the ANSI C84.1 Standard specification for 'Range A': 120V $\pm 5\%$ and 220 V $\pm 5\%$, rounded to the nearest tenth of a kWh [H].

EFFICIENCY LOSSES / HARDWARE VARIATION (P_{Ω})

Efficiency loss is a generic term used for transmission and conversion losses. The transmission losses are due to the internal resistance of the components (EVSE, on-board charger (OBC), wiring harnesses, and RESS). The conversion loss refers to process of transforming the AC input power to a suitable DC power level for PIC. For simplicity, both the transmission and conversion losses are grouped into one generic power term and with an uncertainty, ϵ_{Ω} . The uncertainty represents hardware variation from component-to-component and throughout the life of the vehicle (i.e. end-of-life operation).

The nominal value used for efficiency losses was set to $(1 - 0.90) * P_{WALL}$, with an error band of $\pm 5\%$ (i.e. the system is 85% to 95% efficient, with 90% used as a nominal value;

these values were selected for demonstration purposes and may vary based on the hardware configuration.

ANCILLARY LOADS ($P_{CONTROL}$)

$P_{control}$ represents the power required to control the charging system. Based on the system, $P_{Control}$ may be dependent on a variety of ancillary loads: ECUs, pumps, blowers, and/or LV battery charging. The fluctuation of these ancillary loads from PIC event to PIC event creates additional uncertainty for CT predictions, which will be represented by $\epsilon_{Control}$.

For the purpose of this report, the default control power will be taken as 100W, which is based on 50W to cool the power electronics and 50W to power the ECUs. The error band is asymmetrical: $-25W, +100W$; this is because we assume that the default controller loads were designed to maximize energy efficiency and, as a result, deviations from the default typically demand more power consumption.

USABLE CAPACITY (E_{RESS})

The process of calculating the energy required to reach a full PIC, $(E_{RESS,full} - E_{RESS,0})$ depends on the battery electrochemistry, temperature, usage, and lifecycle. Due to the complexity associated with calculating the State of Charge (SOC), a confidence band of $\pm 5\%$ SOC is assumed, which is represented by ϵ_{RESS} .

The same PHEV RESS capacity used by Scholer, et. al. was used in this study: 8kWh [A].

THERMAL CONDITIONS ($P_{THERMAL}$)

For the purpose of this report, four factors are discussed that may impact the power used for thermal conditioning, $P_{Thermal}$: the Outside Air Temperature (OAT), the RESS Temperature (T_{RESS}), the upper temperature limit for the RESS ($T_{Hot,Lim}$), and the lower temperature limit for the RESS ($T_{Cold,Lim}$). The internal ohmic heat generation caused by charging the RESS, S_{dot} , was ignored due to the low charge rates for Level 1 and Level 2 PIC. Also, to simplify the sensitivity analysis, if thermal conditioning is required, T_{RESS} is assumed to be maintained at the temperature limits throughout the charge process.