An Assessment of Level 1 and Level 2 Electric Vehicle Charging Efficiency

TO INVESTIGATE POTENTIAL APPLICATIONS OF EFFICIENCY MEASURES TO VARIOUS ELECTRIC VEHICLES AND THEIR SUPPLY EQUIPMENT

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Introduction

The integration of Plug-in Electric Vehicles (EVs) in Vermont's transportation sector will bring significant energy related benefits to the state and enable the extensive experience Efficiency Vermont has gained in developing effective efficiency measures to be applied to this sector.

EVs are expected to increase their presence in the next two decades. In Vermont, projections of the number of EVs that will be registered by 2030 have been modeled from a conservative 10,000[1] to more than 100,000[2]. The Vermont Comprehensive Energy Plan (CEP) has set a goal of powering 25% of vehicles in the state from renewable energy sources by 2030 as a step toward the overall goal of 90% of the state's energy use coming from renewable sources by 2050. The CEP 2030 interim goal for reducing petroleum consumption could be met by 150,000 EVs powered from solar, wind, biomass and hydro energy. Vermont is among thirteen states that have adopted regulations requiring auto manufacturers to substantially increase the proportion of low and/or zero emission vehicle sales over the coming years. These regulations are responsible for accelerating the development of advanced technology vehicles such as hybrid-electric, plug-in hybrid electric, full battery electric and fuel cell vehicles, and are helping to rapidly expand the EV market[3]. EV demand may also be accelerated due to the following factors:

- Federal tax credits—currently amounting to as much as $7,500[4]—can be claimed by the buyers or leaseholders of EVs
- EVs offer owners security from gasoline price volatility
- EVs feature improved acceleration and reduced maintenance costs compared to conventional Internal Combustion Engine(ICEs) vehicles

The penetration of EVs in Vermont will dramatically reduce the environmental costs of energy in the state. Transportation is the largest single source of Greenhouse Gas (GhG) emissions and energy consumption in Vermont, because of our high reliance on Internal Combustion Engine (ICE) vehicles to meet the state's mobility needs, our relatively clean grid and small industrial base.[5] EVs can be as much as three times more efficient than traditional ICEs in using energy for propulsion and are capable of recapturing energy through regenerative braking. Furthermore, because EVs use electricity as an energy source, they can be powered by renewable resources. The average Vermont vehicle driven by the average Vermont driver will generate nearly six tons of CO_2 annually while the estimated upstream CO_2 emissions of an EV for the average Vermont driver is less than two tons[6].

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[1] Estimation made by the VT Agency of Natural Resources. Cited in the Vermont Comprehensive Energy Plan 2011.
[2] Dowds, Jonathan, Paul Hines, Chris Farmer, Richard Watts and Steve Letendre. *Plug in Hybrid Electric Vehicle Research Project: Phase II Report*. UVM Transportation Research Center. 2010.
[3] Per email communication with Tom Moye.
[4] Calculated based on kWh capacity of the vehicle battery system
[5] Sears, Justine and Karen Glitman. *The Vermont Transportation Energy Report 2010*. University of Vermont Transportation Research Center. August 2011.
[6] See appendix.

Uncontrolled EV charging may create the need for additional infrastructure and result in longer and higher peak demand. In order to meet this increased load without substantial expansion of generation capacity, it is critical that EV charging be performed as efficiently as possible.

Identifying opportunities for applying efficiency measures to EVs requires analysis of energy usage from the point it flows from the grid to its release in the wheels of the vehicle. This includes the following two primary processes:

- Charging: Storage of electrical energy in the EV battery system
- Driving: Transformation of electrical energy into motion

This study analyzes one aspect of EV charging: the differences between Level 1(120V) and Level 2(240V) charging efficiency.

Study Purpose

This research sought to identify the most efficient means of EV charging and to assess applications for efficiency measures to EV charging infrastructure. The specific objectives of this project were to:

- Determine the differences in efficiency between charging an EV using Level 1 or Level 2 charging equipment

- Determine the influence of ambient weather conditions on electric vehicle charging efficiency

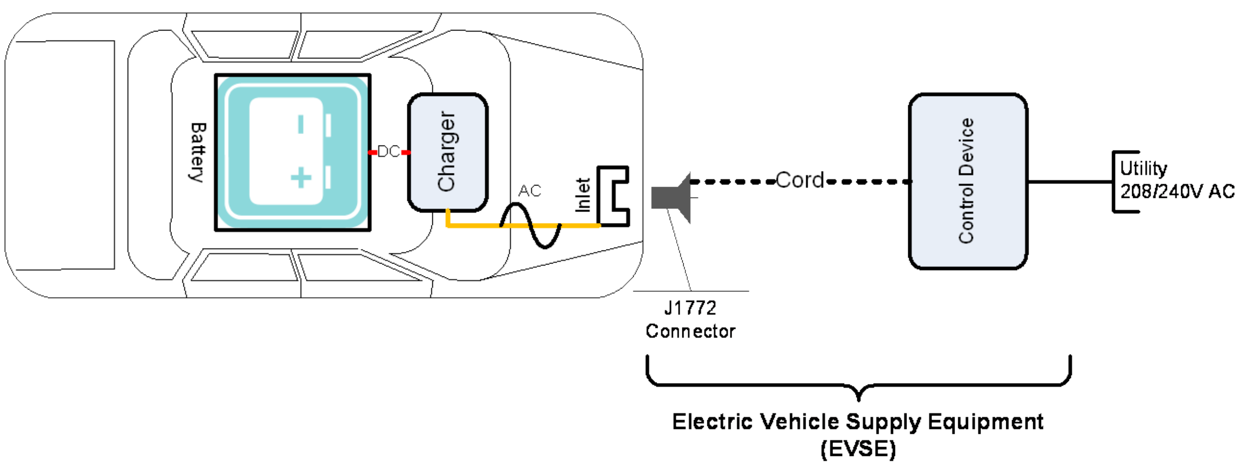
The results of this research may be used to inform EV charging efficiency measures and identify additional research needs as EV technology becomes more widespread in Vermont.

EV Charging Technology Overview

There are two types of Electric Vehicle Supply Equipment (EVSE) presently available in Vermont. Level 1 charging uses a 120V AC connection to a standard residential/commercial branch circuit receptacle capable of supplying 15-20 amps of current. Level 2 charging requires a 208/240V AC connection to supply increased power to the vehicle charging system, which reduces the amount of time required to charge the EV battery. All electric vehicles currently available on the market come with Level 1 chargers but acquiring Level 2 EVSE typically means an additional investment for EV owners.

Both Level 1 and Level 2 charging supply AC power to the vehicle's built-in charger, which then converts the energy to DC for storage in the battery. Figure 1 provides a schematic diagram of the components included in Level 2 EVSE, which consist of the J1772 connector, the cord and the control device connected to the utility grid. Level 1 EVSE operates in a very similar manner.

Figure 1 Electric vehicle charging system



Methodology

INITIAL PROPOSED SCOPE

The initially proposed study sought to compare the efficiency of Level 1 and Level 2 EVSE through the application of a metering program. A sample of EV owners would be asked to collect measurements of the power Level at the utility outlet and at the J1772 connector during charging events. This was expected to enable observation of energy drawn by the EVSE control device.

However, review of existing EVSE research and discussion with vendors indicated the metering program was not worthwhile due to very high efficiencies of these systems which essentially act as switches for the charging circuitry located in the vehicle. The Idaho National Laboratory has tested several EVSE units and found them to be 98% or more efficient[7].

Findings in literature on in-vehicle charging systems revealed some variation in efficiency at different supply voltages (120V versus 208/240V), with higher voltage providing lower resistive loss. One study showed AC/DC power conversion in a plug-in hybrid electric vehicle charger near 95% efficiency at 120V and near 97.5% at 240V.[8] The use of Level 2 charging may also yield greater efficiencies than Level 1 because of the shorter charging times and in turn less power is needed for ancillary battery cooling and charging management systems.

REVISED SCOPE AND METHODOLOGY APPLIED

In early December 2012, we acquired data from FleetCarma that would enable comparison of the global efficiency of Level 1 charging to Level 2 charging and the impacts of climatic conditions on charge efficiency. Data was drawn from a database of real-world electric vehicle performance information collected by FleetCarma using their proprietary C5 Logger. This device plugs directly into the internal diagnostic computer of an EV and enables precise monitoring of the state of charge of the vehicle's battery and the energy entering the vehicle from the J1772 connector (see Figure 1 on previous page).

More than 1,000 unique charging events were analyzed involving a total of 17 electric vehicles. All vehicle data used in this study was from General Motors Chevrolet Volts of the same model year. This resulted in no variation in charging efficiency accruing from differences in the auxiliary systems of different EV makes and models.

The ambient air temperature of each charging event was assigned to each data point to enable analysis of the impact of climatic conditions on charging efficiency. This data was collected through the built in thermal sensors of the Chevrolet Volt.

Of the charging events observed, 48% were performed using Level 1 charging equipment and the remaining 52% using Level 2 equipment. The full FleetCarma report is available upon request.

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[7] Idaho National Lab Electric Vehicle Supply (EVSE) testing. http://avt.inl.gov/evse.shtml. Accessed 12 December 2012.

[8] Deepak Gautam et al. "An Automotive On-Board 3.3 kW Battery Charger for PHEV Application". IEEE Transactions on Vehicular Technology. 2011.

Findings

BASE COMPARISON OF LEVEL 1 AND LEVEL 2 CHARGE EFFICIENCY

On aggregate, Level 2 charging was confirmed to be 2.7% more efficient than Level 1 charging. A mean charge efficiency of 86.4% was observed in Level 2 charge events and Level 1 charge events were shown to be 83.7% efficient on average.

A more granular analysis of the data revealed Level 2 charging to be considerably more efficient than Level 1 charging in "low-energy" charge events—when less than 2 kWh drawn from the grid. Level 2 charging was observed to be 12.8% more efficient on average than Level 1 charging in these instances. In "high-energy" charge events—when greater than 2kWh was drawn from the grid—Level 2 was shown to be more efficient than Level 1 but by the more modest margin of 2.3% on average.

Low-energy charge events were also shown to exhibit a high level of variation in charge efficiency whereas high-energy charge events yielded fairly uniform results.[9] Table 1 below summarizes these findings.

Table 1 Summary of Level 1 vs Level 2 charge efficiency

Charge event dataset	Average Level 2 Charge Efficiency	Average Level 1 Charge Efficiency	Efficiency gain of Level 2 charging
Total combined	86.4%	83.7%	**2.7%**
High energy only (>2 kWh charge)	86.5%	84.2%	**2.3%**
Low energy only (<2 kWh charge)	83.5%	70.7%	**12.8%**

[9] This observation was made in the data analysis provided by FleetCarma in *An Investigation of Level 1 vs. Level 2 Charging Events in Plug-In Vehicles*. Unpublished manuscript. December 2012. Available upon request from the author.

IMPACTS OF CLIMATIC CONDITIONS ON LEVEL 1 AND LEVEL 2 CHARGE EFFICIENCY

Only high-energy charge events were included in the analysis of the impacts of climatic conditions on charging efficiency. This decision was made in order to minimize the interference of unexplained variation on the findings.

Ambient air temperature of charging events was shown to explain approximately 22% of the variation in charging efficiency. Cases in which the temperature was between 53 and 70 degrees Fahrenheit exhibited the highest charge efficiency for both Level 1 and Level 2 charging, with Level 2 charging 2.1% more efficient than level 1 in these conditions. In charge events in which the temperature was less than 53 degrees or greater than 70 degrees the margin of efficiency gains of Level 2 charging was greater at 3.4% and 3.2% respectively[10].

Table 2 Summary of Level 1 vs. Level 2 charge efficiency with climatic variation

Charge event dataset	Average Level 2 Charge Efficiency	Average Level 1 Charge Efficiency	Efficiency gain of Level 2 charging
High energy only (>2kWh charge) between 53^0 F and 70^0 F	87.8%	85.8%	**2.1%**
High energy only (>2kWh charge) and less than 53^0F ambient temperature	87.3%	84.0%	**~3.4%**
High energy only (>2kWh) and greater than 70^0 F ambient temperature	85.3%	82.2%	**~3.2%**

[10] These observations were provided by FleetCarma in *An Investigation of Level 1 vs. Level 2 Charging Events in Plug-In Vehicles*. Unpublished manuscript. December 2012. Available upon request from the authors.

Conclusions

DISCUSSION OF ENERGY SAVINGS OF LEVEL 2 CHARGING

In all scenarios analyzed, Level 2 charging was found to be consistently more efficient than Level 1 charging. Optimum charge efficiency was observed in cases where greater than 2kWh was drawn from the grid and ambient temperature was between 53^0 and 70^0 Fahrenheit. Efficiency gains of Level 2 charging were lowest in these instances. In charge events that occurred under sub optimal conditions the margin of efficiency gains achieved through a switch from level 1 to Level 2 was highest.

Due to the scale of energy demanded by EVs, improvements in charging efficiency of a few percentage points can result in large energy savings. Therefore, efficiency measures may be warranted regardless of the expected charging conditions particularly if the costs of installation are sufficiently low. Table 1 below provides an example of the energy consumption of the Chevrolet Volt[11].

Table 3 Summary of projected EV energy usage

Energy consumption of the Chevrolet Volt	
Miles/kWh	2.86
Projected annual energy consumption in kWh	4466.64[12]
Projected lifetime energy consumption in kWh	34,965.03[13]

RECOMMENDED APPLICATIONS FOR CHARGING EFFICIENCY MEASURES

Home charging

Charging in residential settings typically occurs under optimal conditions for charge efficiency. Vehicles are often kept indoors in garages where ambient temperature variation is relatively moderate. Home charging also typically occurs over long periods overnight and therefore greater than 2 kWh of energy is stored in the vehicle's battery in each charge event.

Based on the data analyzed in this study and the expected conditions of residential charge events, Level 2 charging would likely yield approximately 2.1% efficiency gains. Under the assumptions used in Figures 2 and 3, this would amount to an estimated 119 kWh energy savings annually and 928 kWh energy savings over the lifetime of a vehicle. At minimum the cost of a Level 2 EVSE retrofit and installation would be over $500 and the total value of kWh savings at current prevailing energy prices in Vermont would be around $150. Further analysis would be required to determine if Level 2 home charging would be eligible for financial incentives.

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[11] Models of comparable class to the Chevrolet Volts used in this study that are currently on the market range in operational efficiency from as high as 3.57 miles/kWh to as low as 2.27 miles/kWh. The gains of shifting from Level 1 to Level 2 charging therefore will be influenced by the fuel efficiency of the vehicles consumers choose to purchase.
[12] Based on an average of 1.10 vehicle per VT licensed driver and 14038 vehicle miles traveled per year per VT licensed driver. Drawn from: Sears, Justine and Karen Glitman. *The Vermont Transportation Energy Report 2010*. University of Vermont Transportation Research Center. August 2011.
[13] Based on 100,000 mile guarantee offered by the manufacturer of the Chevrolet Volt.

Public charging

Public charging typically occurs under sub-optimal conditions for charge efficiency. Vehicle owners commonly use public charging locations to gain a small amount of additional energy but not to reach a full charge. Public charging infrastructure is also often located in parking lots which are directly exposed to the elements and are most subject to extreme variations in ambient temperature.

Efficiency measures would yield the greatest benefit in public charging locations where expected charging times are the lowest and frequency of usage is the highest. Table 4 provides an example of the estimated efficiency gains of Level 2 public charging in a retail commercial environment.

Table 4 Example of Level 2 efficiency gain in retail parking lot setting

Healthy Living Natural Market EVSE Location	
Average charge event duration	~41 minutes[14]
Level 1 energy transfer in 41 minute charge	Less than 2 kWh
Level 1 efficiency in <2kWh charge events	70.7%
Level 2 energy transfer in 41 minute charge	Greater than 2 kWh
Level 2 average efficiency in >2kWh charge events	86.5%
Level 2 efficiency gain under typical charging conditions	**15.8%**

The energy saving potential of Level 2 charging in public locations is expected to grow in line with the growth in EV market penetration. In the case of Healthy Living Natural Market, the monthly number of charge events at this dual port Level 1/Level 2 charging station increased by more than 300% during the period observed between October 2011 and September 2012. If these trends continue, there may come a time when measures to incentivize Level 2 charging retrofits or new Level 2 charging infrastructure at retail locations might be cost-effective.

Two studies currently under way at VEIC are examining siting criteria for public charging stations and projecting usage at a variety of location types. Future utilization will be estimated based on current usage trends, EV market growth projections and travel patterns among other factors. These studies will provide guidance to future efforts to determine if Level 2 charging might produce positive net-benefits and thus be eligible for financial incentives.

[14] Data provided by Green Mountain Power, September 24, 2012. Email from Don Lorraine to Evan Forward. Data collection period was between October 20, 2011 to September 22, 2012.

Opportunities for further study

Transportation electrification will require investments to accommodate the demands and benefits EVs place on the power grid. There may be significant opportunity to implement measures that reduce the total energy demands of EVs and enable EVs to serve as grid resources that improve the efficiency, reliability and overall operating costs of electricity generation and transmission. Further study is needed to explore the technical implications, policy needs, and net economic benefits of these measures. Five recommended areas for further exploration include:

- EV efficiency based measures
- EV performance based efficiency measures
- Rate based incentives for EV smart charging
- Incentives for EV grid service provision
- Efficiency comparison of single and three phase charging

EV EFFICIENCY BASED MEASURES

As shown in the appendix of this report, there is considerable variation in the efficiency of EV models currently on the market. The choice to purchase a 2012 Scion IQ EV instead of a 2012 Coda Sedan EV, for example, could be the difference of more than 2,000 kWh consumed per year based on typical Vermont travel patterns and EPA vehicle efficiency estimates[15]. Under real-world conditions variation in the efficiency of EVs may be even greater, particularly in regions such as Vermont with highly variable terrain and climatic conditions. If some EV manufacturers choose to diverge from Lithium Ion battery technology in the future, even more variation may emerge with regards to overall EV energy efficiency.

Currently, federal tax incentives for EVs are calculated based on the total capacity of the battery system rather than overall efficiency with which the EV uses energy. Just as federal and state governments have intervened in the auto industry to compel producers to manufacture vehicles with higher fuel efficiency, state intervention in markets for EVs—including regulatory action or incentive programs designed to support markets for high efficiency EVs—may become an appropriate means of achieving energy savings.

[15] See appendix

EV PERFORMANCE BASED EFFICIENCY MEASURES

Efficiency initiatives designed to influence EV owners to drive less and drive more efficiently may be a cost effective means of garnering energy savings. Transportation efficiency programs currently under development and already active could be leveraged to implement such measures including the following:

Residential Transportation Energy Assessment Program

This meter-loan program pilot study is being carried out by the VEIC Transportation Efficiency group with funding from the High Meadows Fund. Modeled loosely on Efficiency Vermont's Watt Meter program, this study seeks to evaluate the effectiveness of a program to loan out meters to Vermonters for performing transportation energy assessments on gasoline fueled vehicles. The program hopes to result in adoption of more efficient driving techniques by enabling observation of the effect the way one operates a vehicle has on fuel consumption. If proven effective in lowering driver energy consumption, this program could be easily expanded.

GoVermont

This state transportation demand management program offers an array of services and initiatives designed to encourage reductions in transportation energy usage. Incentives such as free or reduced cost bus passes and subsidized participation in vanpool programs for EV owners may be able to generate measurable reduction in energy use and could be easily integrated into GoVermont online and offline programming.

RATE BASED INCENTIVES FOR EVS

The implementation of Advanced Metering Infrastructure (AMI) and multi-channel metering can enable EV specific rate structures to incentivize smart charging strategies that reduce EV charging during peak demand periods and contribute to a more balanced load shape on the grid. Two specific models that may warrant further study include time of use rates and voluntary demand response rate based incentives.

Time of use rates

The implementation of multi-channel metering can enable the sub-metering of EV charging and in turn the application of EV specific rate structures to incentivize off peak charging. By using rate schedules that encourage charging during specific times, this strategy could help avoid demand spikes during peak hours and fill load valleys resulting in reduced costs of overall grid operation.

Demand response rate based incentives

The implementation of specialized AMI may enable implementation of demand response programs in which—in return for lower rates—EV owners could volunteer to allow grid operators to directly modulate the flow of electricity to charging equipment in response to changes in demand on the grid. Programs such as this may be structured so that EV owners receive a lower rate and grid operators' benefit on net from EV charging through the load balancing this would allow. This may result in incentives for EV ownership and lower utility rates overall.

INCENTIVES FOR EV GRID SERVICE PROVISION

Repurposing of EV battery systems to provide ancillary services to the grid has potential to increase grid stability and lower overall costs of grid operation. Through the implementation of AMI and the retrofitting of EV battery systems to allow bi-directional flow of electricity to and from the grid, EVs could be enabled to serve grid regulation functions or as backup in the event of short term supply shortages. Measures to compensate EV owners for allowing grid operators use of their battery systems for these purposes may be a cost effective means of reducing electricity costs.

EFFICIENCY COMPARISON OF SINGLE AND THREE PHASE CHARGING

Level 2 EVSE is capable of managing both single and three phase electric power whereas Level 1 EVSE can only be used with single phase electric power. Three phase electric circuits are typically used for delivering power to large loads and offer a number of advantages over single phase including the potential for higher efficiency of energy transfer. Additional research into the energy saving potential of three phase Level 2 charging is needed to understand the full efficiency gains achievable through favoring this charging method. Comparing the efficiency of single phase and three phase Level 2 charging would require simultaneously metering the energy loss between the power outlet and vehicle battery system as well as loss between the transmission lines and the outlet.

Currently, it is rare for households to have access to three phase power but it is not uncommon in commercial settings. As charging infrastructure becomes a more common consideration during new construction, an understanding of the efficiency gains found in using three phase electric power for EV charging could help to inform property owner decisions regarding both EVSE technology options and building circuitry configuration.

Appendix

Transportation need and CO2 emission status quo	
Vehicles per VT licensed driver[16]	1.10
Vehicle miles traveled per VT licensed driver[17]	14038
Vehicle miles traveled per VT licensed driver per vehicle	12534
Pounds of CO2/Mile 2010 Average VT ICE vehicle[18]	0.90
Miles/gallon equivalent Average VT ICE vehicle[19]	28
CO2 Emissions of Selected EVs and comparison to average VT ICE	
Total Pounds CO2/year Average VT ICE vehicle	11306
Pounds of CO2/Mile[20] 2012 Scion IQ EV[21] (High efficiency EV)	0.26
Pounds of CO2/Mile 2012 Coda Sedan EV (Low efficiency EV)	0.44
Total CO2/year 2012 Scion IQ EV	3309
Total CO2/year 2012 Coda Sedan EV	5515
Total annual CO2 avoided for 2012 Scion IQ EV compared to status quo	7997
Total annual CO2 avoided for 2012 Coda Sedan EV compared to status quo	5791
Projected annual EV energy consumption selected models	
Mile/kWh 2012 Scion IQ EV	3.85
Mile/kWh 2012 Coda Sedan EV	2.27
Estimated total kWh/year for VT Driver 2012 Scion IQ EV	3510
Estimated total kWh/year for VT Driver 2012 Coda Sedan EV	5766

[16] Sears, Justine and Karen Glitman. *The Vermont Transportation Energy Report: Vermont Clean Cities Coalition.* University of Vermont Transportation Research Center. August 2011.
[17] Ibid.
[18] US Department of Energy estimated tailpipe and upstream CO2 emissions. www.fueleconomy.gov accessed 17 December 2012.
[19] Ibid, Sears and Glitman 2011.
[20] http://www.fueleconomy.gov/feg/Find.do?action=sbs&id=33307. Accessed 17 December 2012
[21] The Scion IQ EV and the Coda Automotive Sedan EV were selected to demonstrate the efficiency spectrum within EVs of roughly analogous class. Scion IQ EV offers 73 cubic feet of passenger capacity and the Coda Sedan EV offer 72 cubic feet of passenger volume.