SUMMARY

Higher penetration of renewable energy in islands, isolated, and export-constrained power grids, and in the absence of sizable energy storage, may result in high levels of curtailment (or spillage) of essentially zero variable cost renewable energy, particularly during periods of low electricity demand.

The study reported in this paper evaluated the capacity of electric vehicle charging on capturing renewable energy in Oahu’s power grid that would be otherwise curtailed, by considering a number of renewable penetration scenarios based on different levels of solar and wind power deployments. Under each of the scenarios considered, performance and impact of a number of different EV charging profiles were evaluated. The profiles ranged from the simplest uniform charging which represents the worst (or least flexible) option to “the Best We Can Do” charging which represents the best (and most flexible) option, i.e., aligning the charging periods with the expected times of curtailment. These two extreme profiles provide the two bookends of the analysis. Four other profiles that were considered, represent relatively more realistic scenarios whose impacts are somewhere between the first and last profile.

This paper describes the methodology and assumptions of the study, which used the GE Multi-Area Production Simulation (GE MAPS) software program (a production costing model) to simulate the underlying power system and to determine the amount of curtailed renewable energy without EV charging and with different EV charging profiles.

The underlying study was sponsored by Hawaii Natural Energy Institute (HNEI) on behalf of The Research Corporation of the University of Hawaii (RCUH).

KEYWORDS

Renewable Energy, Wind, Solar, Curtailed Energy, Electric Vehicle, EV Charging, Smart Charging
INTRODUCTION

Integration of higher levels of renewable energy into a power grid may be accompanied with higher levels of renewable energy curtailment (i.e., spillage) during periods of low electricity demand, particularly in smaller and isolated systems or in export-constrained areas.

One idea to reduce renewable energy curtailment is to foster higher deployment of Electric Vehicles (EVs), which with smart scheduling of EV charging, would be expected to increase demand for electricity during times of high curtailment. To investigate this idea further, this study, through the modeling of an actual power system, investigated the impact of different EV charging profiles on the reduction of the curtailed renewable energy.

The study considers a number of renewable penetration scenarios based on different levels of solar and wind power deployments. Under each of these scenarios, performance and impact of a number of different EV charging profiles were evaluated. The profiles ranged from the simplest uniform charging representing the worst or least flexible option to charging time aligned with curtailment time representing the best or most flexible option (i.e., or “the Best We Can Do” and “perfect tracking” profile). These two profiles provide the two bookends of the analysis. Four other profiles were considered, representing relatively more realistic scenarios whose impact were somewhere between these two extreme profiles.

METHODOLOGY

General Electric’s Multi Area Production Simulation (GE MAPS) software program was used for the simulation of renewable scenarios under the different EV charging profiles. GE MAPS performs daily unit commitment and hourly economic dispatch of generation to meet hourly load plus operating reserves. The year considered in the study was 2015. Inputs to GE MAPS include unit-by-unit thermal and renewable generation characteristics, load projections, fuel prices, transmission limits, and generation and transmission constraints, and other operational and economic parameters. GE MAPS outputs include hourly plant by plant electricity production, renewable energy curtailment, variable cost of electricity production, criteria pollutant and greenhouse gas emission volumes and costs, fuel consumption, power flows, and other detailed information.

The main approach to determine EV Charging profiles, or schedules, was to extrapolate limited driving survey data in Oahu into EV Charging behavioral preferences, and then using the resulting hourly increases in electricity demand to modify the system’s assumed hourly electric load. The study did not explicitly model types of EV or specific EV fleet sizes, vehicle types, mixes, which is outside the scope of this work, and actually not necessary for the purposes of this study.

The analysis was based on deterministic EV schedules and did not consider probabilistic behavior or perform any stochastic analyses. That could be the subject of future research. The purpose was to provide an understanding of the system-wide impacts and ability to limit curtailing renewable generation under a number of simple EV Charging profiles, to help policy makers design appropriate incentive and pricing programs that would best achieve higher utilization of renewable resources in Oahu.

Renewable Penetration Cases

This study was built upon the production simulation models developed for the Oahu Wind Integration and Transmission Study (OWITS) and Hawaii Solar Integration Study (HSIS), but with wind and solar generation resources increased to 1000 MW. The system model was derived from OWITS Scenario 5, which included 500 MW of wind generation and 100 MW of solar generation connected to the Oahu power grid.
As shown in the following table, the study considered four Base Cases initially with no EV deployment, representing four different mixes of solar and wind power installations in terms of their total MW capacity. Also shown in the table is the amount of curtailed renewable energy in each scenario in the absence of EV charging.

### Table 1: Available and Curtailed Renewable Energy in each of the Four Base Cases

<table>
<thead>
<tr>
<th>Base Cases</th>
<th>Wind (MW)</th>
<th>Solar (MW)</th>
<th>Total (MW)</th>
<th>Unit &gt;</th>
<th>Available Wind</th>
<th>Available Solar</th>
<th>Available Total</th>
<th>Curtailed Wind</th>
<th>Curtailed Solar</th>
<th>Curtailed Total</th>
<th>Curtailed / Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>GWh</td>
<td>1,931.8</td>
<td>174.1</td>
<td>2,105.9</td>
<td>209.7</td>
<td>0.1</td>
<td>209.8</td>
<td>10.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Total</td>
<td>91.7%</td>
<td>8.3%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>0.0%</td>
<td>100.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td>Base 2</td>
<td>700</td>
<td>300</td>
<td>1000</td>
<td>GWh</td>
<td>2,648.0</td>
<td>530.1</td>
<td>3,178.1</td>
<td>681.1</td>
<td>54.6</td>
<td>735.7</td>
<td>23.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Total</td>
<td>83.3%</td>
<td>16.7%</td>
<td>100.0%</td>
<td>92.6%</td>
<td>7.4%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Base 3</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>GWh</td>
<td>1,931.8</td>
<td>886.1</td>
<td>2,817.9</td>
<td>356.8</td>
<td>43.9</td>
<td>400.7</td>
<td>14.2%</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Total</td>
<td>68.6%</td>
<td>31.4%</td>
<td>100.0%</td>
<td>89.1%</td>
<td>10.9%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Base 4</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>GWh</td>
<td>1,931.8</td>
<td>530.1</td>
<td>2,461.9</td>
<td>257.3</td>
<td>4.2</td>
<td>261.5</td>
<td>10.6%</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Total</td>
<td>78.5%</td>
<td>21.5%</td>
<td>100.0%</td>
<td>98.4%</td>
<td>1.6%</td>
<td>100.0%</td>
<td>10.6%</td>
</tr>
</tbody>
</table>

### EV Charging Profiles

Under each of these Base Cases, performance and impact of the following six different EV charging profiles were evaluated.

- **Type A** - Annual Uniform Charging Profile: Uniform EV charging all hours of the year equal to the hourly average of Base Case curtailed renewable energy.
- **Type B** – Annual Perfect Tracking: Same daily EV Charging load shape based on the annual average of curtailed renewable energy for each hour of day.
- **Type C** – Profile 1: 30% of daily charge during Day Period (7 AM to 5 PM) and 70% of daily charge during Night Period (5 PM to 7 AM).
- **Type D** – Profile 2: 30% of daily charge during On-Peak Period (7 AM to 5 PM), 0% of daily charge during the Critical Peak Period (5 PM to 9 PM), and 70% of daily charge during Off-Peak Period (9 PM to 7 AM).
- **Type E** – Profile 3: 85% Evening Profile: 15% of daily charge during Day Period (7 AM to 5 PM), 0% of daily charge during the Critical Peak Period (5 PM to 9 PM), and 85% of the daily charge during the Night Period (9 PM to 7 AM).
- **Type F** – Daily Perfect Tracking: Daily EV Charging load shape proportional to that day’s curtailed energy load shape on an hour-by-hour basis.

The EV charging profiles are shown in the following figure. The first profile is the simplest, providing the worst option. The last profile is the “Best We Can Do”, providing the best option. These two profiles provide the two bookends of the analysis. The other four profiles represent relatively more realistic scenarios whose impact is somewhere between the first and last profile. To enable comparison across the Base Cases and profiles (i.e. scenarios), two key assumptions are made as follows.

- Total annual electricity demand by the EV fleet in each EV Charging scenario was set equal to the annual curtailed renewable energy in the corresponding Base Case.
Although the hourly shape of the EV Charging schedule could change from day to day depending on actual EV usage, the total daily EV Charging electricity demand was assumed to be the same every day, and therefore, was set equal to $\frac{1}{365}$th of the annual EV charging electricity demand.

The second assumption is based on the view that the daily EV Charging patterns can be influenced by regulation, incentives, and pricing, but the daily driving needs of individual drivers are less likely to change from day to day (study ignored weekend versus weekday driving patterns).

Figure 1: Hourly Patterns of EV Charging Profiles
The following figure presents the amount of curtailed wind and solar energy in each Base Case captured under different EV charging profiles (in terms of reduction of curtailed energy relative to curtailed energy in the absence of EV charging).

![Figure 2: Renewable Energy Curtailment by EV Charging Profile]

It can be readily observed that the lowest level of curtailment (or highest level of avoided curtailment) occurs under the Type B or Annual Perfect Tracking EV Charging profiles within each wind and solar generation mix category. The order of effectiveness (measured based on avoided curtailment of renewable energy) of the EV Charging profiles is from best to worst:

1. Daily Perfect Tracking (Type F)
2. Annual Perfect Tracking (Type B)
3. Annual Profile 2 / 85% Evening Profile (Types D and E)
4. Annual Profile 1 (Type C)
5. Annual Uniform Charging (Type A)

Although unrealistic to force daily EV Charging to follow the hypothetical pattern of potentially curtailed renewable energy, the Daily Perfect Tracking sets the upper limit on what can be achieved. The performance under Annual Profile 2 (i.e., the 70% evening charge) and 85% Evening Profile come very close to the upper limit.

These results are to be expected, since as the name indicates, the Annual Perfect Tracking provides the closest match to the daily pattern of renewable energy curtailment in the corresponding Base Case, even if the pattern and daily amount of EV Charging does not change from day to day. Annual Profile 2 (having on-peak and off-peak EV charging, but no charging during the critical peak periods) comes closest to the Annual Perfect Tracking. The Annual Uniform Charging simply represents a constant increase in demand each hour of each day of the year, and hence has absolutely no alignment with the hourly renewable energy curtailment in the corresponding Base Case, and hence, is the least capable in capturing the potentially curtailed renewable energy.
In Case 1 related scenarios the maximum reduction in curtailed renewable energy is 46.70% under the Daily Perfect Tracking. As a more realistic scenario, the Annual Profile 2 (i.e., 70% evening EV Charging, with zero charging during critical peak period) achieved a 29.81% reduction. Comparable reductions are 55.35% and 45.43%, respectively for Case 2 related scenarios, 49.63% and 35.83%, respectively for Case 3 related scenarios, and 46.26% and 32.88%, respectively for Case 4 related scenarios.

The following figure depicts hourly dispatch of generation resources during the week with the hour of least load energy.

![Figure 5: Hourly Dispatch during Week with the Hour of Least Load Energy](image)

**LIMITS TO CAPTURE OF CURTAILED RENEWABLES BY EV CHARGING**

The Best We Can Do profile is the Daily Perfect Tracking. This profile assumes that by keeping total daily EV Charging the same from day to day, the hourly EV Charging would change proportionally to the hourly curtailed energy of the corresponding Base Case. In other words, the hourly pattern of the EV Charging for each day is based on taking the hourly pattern of the curtailed energy of the corresponding Base Case for that day, and scaling it up or down to get the total Daily EV Charge. Under the assumption of fixed total daily EV Charge, this hourly EV Charging profile that tracks that day’s curtailed energy profile of the corresponding Base Case, would capture the maximum possible curtailed energy. For days where there are no hours with any curtailed energy, the Daily Perfect Tracking profile would be a uniform charging profile.

The Daily Perfect Tracking has the following characteristics.

- Total Annual EV Charging is equal to the total annual curtailed renewable energy of the corresponding Base Case.
- Total Daily EV Charging does not change from day to day and is equal to the daily average of the curtailed energy of the corresponding Base Case.
- Hourly EV Charging does change from hour to hour within a day, and follows the hourly pattern (i.e., shape) of same day curtailed energy of the corresponding Base Case.
Figure 3: Chronological Scatter Plot of Daily Energy Curtailment and Daily 100% EV Charging

Figure 4: Duration Curve of Base Case 2 Daily Curtained Energy with 100% EV Charging

The duration curve is constructed based on sorting the daily curtailed energy from highest to lowest across the 365 days in the year. The plot also includes the daily level of EV Charging, which is constant from day to day.

This plot is a telling representation of the ability of EV Charging to capture potentially curtailed renewable energy. There are three distinct areas on the plot:

- **Area representing unused curtailed energy:** this is the area identified by the green box. Any curtailed energy above the EV Charging demand goes unused (i.e., remains curtailed), since at those hours the EV Charging demand is not sufficient to use up all the potentially curtailed energy.

- **Area representing used curtailed energy:** this is the area identified by the blue box. EV charging demand can absorb portions of the curtailed energy. The size of this area represents the potential reduction in renewable energy curtailment.

- **Area representing additional thermal energy needed:** this is the area represented by the red box. During these hours, the EV Charging demand is greater than the curtailment. Hence, additional energy from thermal generation is needed to meet portions of the EV charging not
met by renewable energy. Therefore, any realistic EV charging schedule is expected to increase thermal energy generation compared to the corresponding No EV Base Case.

KEY FINDINGS

The key findings of this study are listed below.

- Under the assumption that the total annual EV Charging is equal to the total annual curtailed energy of the Base Case, and that daily EV Charging is the same every day; it is impossible for EV Charging to capture all the curtailed renewable energy in any of the 24 EV Charging scenarios.

- The maximum curtailed renewable energy can be captured under the Daily Perfect Tracking, which is the best that can be done under our EV Charging assumptions.

- Annual EV Charging at higher levels than the assumed annual curtailed energy limit captures more of the curtailed energy, but at the same time results in demand for more thermal energy, since during some hours there is more demand for energy to charge EVs than is available through renewable resources.

- The Type A - Annual Uniform Charging - results in the smallest reduction in curtailed energy – and provides a worst case bookend to the analysis.

- In contrast, the Type F - Daily Perfect Tracking - results in the largest reduction in curtailed energy, and provides a best case bookend to the analysis.

- The more realistic Type D - Annual Profile 2 (70% daytime charging, 0% critical peak time charging, and 30% nighttime charging) - comes very close to the Annual Perfect Tracking in terms of capturing potentially curtailed renewable energy and other system-level impacts such as system production costs.

- All EV Charging scenarios result in both higher thermal generation and capture of renewable generation (i.e., less curtailment) than the no EV charging scenario for the corresponding Base Case.

NOTE

Due to space limitations, this paper presents the results of only a portion of the underlying study. For information on additional modeling and sensitivities performed in the study, please consult the reference listed in the bibliography.

BIBLIOGRAPHY