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Prepared by:
GE Energy Consulting

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Hawai‘i Natural Energy Institute

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Oahu Electric Vehicle Charging Study

Prepared for:

The Research Corporation of the University of Hawaii / Hawaii Natural Energy Institute

Prepared by:

GE Energy Consulting

June 10, 2013
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Foreword

This report was prepared by General Electric International, Inc. (GE); acting through its Energy Consulting, based in Schenectady, NY, and submitted to Hawaii Natural Energy Institute (HNEI) on behalf of The Research Corporation of the University of Hawaii (RCUH). Technical and commercial questions and any correspondence concerning this document should be referred to:

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# Acronyms and Nomenclatures

<table>
<thead>
<tr>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMI</td>
<td>Advanced Metering Infrastructure</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage Systems</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
<tr>
<td>DR</td>
<td>Demand Response</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>EMS</td>
<td>Energy Management System</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>ES</td>
<td>Energy Storage</td>
</tr>
<tr>
<td>GE</td>
<td>General Electric International, Inc., and GE Energy Consulting</td>
</tr>
<tr>
<td>GW</td>
<td>Gigawatt</td>
</tr>
<tr>
<td>GWh</td>
<td>Gigawatt hour</td>
</tr>
<tr>
<td>HNEI</td>
<td>Hawaii Natural Energy Institute</td>
</tr>
<tr>
<td>HSIS</td>
<td>Hawaii Solar Integration Study</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt hour</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>MWh</td>
<td>Megawatt hour</td>
</tr>
<tr>
<td>OWITS</td>
<td>Oahu Wind Integration and Transmission Study</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RCUH</td>
<td>The Research Corporation of the University of Hawaii</td>
</tr>
<tr>
<td>TOU</td>
<td>Time of Use</td>
</tr>
<tr>
<td>VOC</td>
<td>Variable Operating Costs</td>
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</table>
Executive Summary

Integration of higher levels of renewable energy into Oahu's power grid, in addition to the many long-term societal, environmental, and economic benefits, is also expected to have some adverse operational and economic impacts. One such impact, and the focus of this study, is the potential for curtailment (i.e., spillage) of renewable energy during periods of high electricity supply and low electricity demand, which is accentuated in small and isolated systems such as Oahu's power grid.

One idea to reduce renewable energy curtailment is to foster higher deployment of electric vehicles on the island, which with smart scheduling of Electric Vehicle (EV) charging, is expected to increase demand for electricity during times of high curtailment. To investigate this idea further, this study, through the modeling of the Oahu power system, quantifies the impact of different EV charging profiles on the operation of the Oahu electric power grid and on the reduction of the curtailed renewable energy.

The study considers four initial Base Cases with no EV deployment, representing four different mixes of solar and wind power installations in terms of their total MW capacity. The Base Cases include:

- Base Case 1: 500 MW of Wind + 100 MW of Solar
- Base Case 2: 700 MW of Wind + 300 MW of Solar
- Base Case 3: 500 MW of Wind + 500 MW of Solar
- Base Case 4: 500 MW of Wind + 300 MW of Solar

Under each of these Base Cases, performance and impact of the following six different EV charging profiles are 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 during each hour of day.
- Type C – Profile 1: 30% of daily charge during Day Period (8 AM to 5 PM, inclusive) and 70% of daily charge during Night Period (6 PM to 7 AM, inclusive).
- Type D – Profile 2: 30% of daily charge during On-Peak period (8 AM to 5 PM, inclusive), 0% of daily charge during the Critical Peak Period (6 PM to 9 PM, inclusive), and 70% of daily charge during Off-Peak period (10 PM to 7 AM, inclusive).
- Type E – Profile 3: 85% Evening Profile: 15% of daily charge during Day Period (8 AM to 5 PM, inclusive), 0% of daily charge during the Critical Peak Period (6 PM to 9 PM, inclusive), and 70% of daily charge during Off-Peak period (10 PM to 7 AM, inclusive).
PM, inclusive, and 85% of the daily charge during the Night Period (10 PM to 7 AM, inclusive).

- Type F – Daily Perfect Tracking: Daily EV charging load shape proportional to that day’s curtailed energy load shape of the No EV Base Case.

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.

GE’s Multi Area Production Simulation (GE MAPS) software program was used for the simulation of the first four profiles. The last two profiles are analyzed with spreadsheet post-processing of the GE MAPS output from the base cases.

GE MAPS performs hourly economic dispatch of generation to meet hourly load plus operating reserves. GE MAPS is typically run for a 20 to 30 year time horizon, but this study only considers the year 2015. Inputs to GE MAPS include unit by unit generation plant characteristics, load projections, fuel prices, transmission limits, and any generation and transmission constraints, among other. GE MAPS outputs include hourly plant by plant electricity production, renewable energy curtailment, variable cost of electricity production, emission volumes and costs, fuel consumption, power flows, and other detailed information for the entire modeling time horizon.

To enable comparison across the Base Cases and profiles (i.e. scenarios), two key assumptions are made:

- Total annual electricity demand by the EV fleet in each EV charging scenario is 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, is set equal to 1/365th 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 (we are ignoring weekend versus weekday driving patterns).

Different EV charging profiles are compared to the base cases and the other profiles based on their impact on various system attributes, including reducing the base case curtailment, system level thermal generation, production costs, fuel consumption, and emissions.

Key modeling results are summarized in the following table:
### Table 1: Curtailed Wind and Solar Energy under Different EV Charging Scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>EV Profile</th>
<th>Wind (MW)</th>
<th>Solar (MW)</th>
<th>Total (MW)</th>
<th>Available Solar/Wind (GWh)</th>
<th>Curtailment Total (GWh)</th>
<th>Curtailment As % Of Solar/Wind</th>
<th>Curtailment Reduction From the Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1 No EV</td>
<td>No EV</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>2,105.9</td>
<td>209.8</td>
<td>9.96%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Base 1 EV A</td>
<td>Annual Uniform Charging</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>2,105.9</td>
<td>169.9</td>
<td>8.07%</td>
<td>19.01%</td>
</tr>
<tr>
<td>Base 1 EV B</td>
<td>Annual Perfect Tracking</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>2,105.9</td>
<td>128.6</td>
<td>6.11%</td>
<td>38.71%</td>
</tr>
<tr>
<td>Base 1 EV C</td>
<td>Annual Profile 1</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>2,105.9</td>
<td>164.6</td>
<td>7.82%</td>
<td>21.55%</td>
</tr>
<tr>
<td>Base 1 EV D</td>
<td>Annual Profile 2</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>2,105.9</td>
<td>147.2</td>
<td>6.99%</td>
<td>29.81%</td>
</tr>
<tr>
<td>Base 1 EV E</td>
<td>85% Evening Profile</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>2,105.9</td>
<td>138.2</td>
<td>6.56%</td>
<td>34.12%</td>
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<tr>
<td>Base 1 EV F</td>
<td>Daily Perfect Tracking</td>
<td>500</td>
<td>100</td>
<td>600</td>
<td>2,105.9</td>
<td>111.8</td>
<td>5.31%</td>
<td>46.70%</td>
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<td>Base 2 No EV</td>
<td>No EV</td>
<td>700</td>
<td>300</td>
<td>1000</td>
<td>3,178.1</td>
<td>735.7</td>
<td>23.15%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Base 2 EV A</td>
<td>Annual Uniform Charging</td>
<td>700</td>
<td>300</td>
<td>1000</td>
<td>3,178.1</td>
<td>440.2</td>
<td>13.85%</td>
<td>40.17%</td>
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<tr>
<td>Base 2 EV B</td>
<td>Annual Perfect Tracking</td>
<td>700</td>
<td>300</td>
<td>1000</td>
<td>3,178.1</td>
<td>399.4</td>
<td>12.57%</td>
<td>45.71%</td>
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<tr>
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<td>700</td>
<td>300</td>
<td>1000</td>
<td>3,178.1</td>
<td>441.6</td>
<td>13.89%</td>
<td>39.97%</td>
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<tr>
<td>Base 2 EV D</td>
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<td>700</td>
<td>300</td>
<td>1000</td>
<td>3,178.1</td>
<td>401.4</td>
<td>12.63%</td>
<td>45.43%</td>
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<td>300</td>
<td>1000</td>
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<td>406.4</td>
<td>12.79%</td>
<td>44.75%</td>
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<td>700</td>
<td>300</td>
<td>1000</td>
<td>3,178.1</td>
<td>343.2</td>
<td>10.80%</td>
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<td>Base 3 No EV</td>
<td>No EV</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>2,817.9</td>
<td>400.7</td>
<td>14.22%</td>
<td>0.00%</td>
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<tr>
<td>Base 3 EV A</td>
<td>Annual Uniform Charging</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>2,817.9</td>
<td>275.8</td>
<td>9.79%</td>
<td>31.16%</td>
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<tr>
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<td>Annual Perfect Tracking</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>2,817.9</td>
<td>239.9</td>
<td>8.51%</td>
<td>40.13%</td>
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<tr>
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<td>Annual Profile 1</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>2,817.9</td>
<td>281.0</td>
<td>9.97%</td>
<td>29.86%</td>
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<tr>
<td>Base 3 EV D</td>
<td>Annual Profile 2</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>2,817.9</td>
<td>257.2</td>
<td>9.13%</td>
<td>35.81%</td>
</tr>
<tr>
<td>Base 3 EV E</td>
<td>85% Evening Profile</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>2,817.9</td>
<td>263.8</td>
<td>9.36%</td>
<td>34.17%</td>
</tr>
<tr>
<td>Base 3 EV F</td>
<td>Daily Perfect Tracking</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>2,817.9</td>
<td>201.8</td>
<td>7.16%</td>
<td>49.63%</td>
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<tr>
<td>Base 4 No EV</td>
<td>No EV</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>2,461.9</td>
<td>261.5</td>
<td>2.64%</td>
<td>0.00%</td>
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<tr>
<td>Base 4 EV A</td>
<td>Annual Uniform Charging</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>2,461.9</td>
<td>198.3</td>
<td>2.48%</td>
<td>24.16%</td>
</tr>
<tr>
<td>Base 4 EV B</td>
<td>Annual Perfect Tracking</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>2,461.9</td>
<td>166.7</td>
<td>2.48%</td>
<td>36.25%</td>
</tr>
<tr>
<td>Base 4 EV C</td>
<td>Annual Profile 1</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>2,461.9</td>
<td>195.9</td>
<td>2.52%</td>
<td>25.08%</td>
</tr>
<tr>
<td>Base 4 EV D</td>
<td>Annual Profile 2</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>2,461.9</td>
<td>175.5</td>
<td>2.52%</td>
<td>32.88%</td>
</tr>
<tr>
<td>Base 4 EV E</td>
<td>85% Evening Profile</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>2,461.9</td>
<td>170.4</td>
<td>2.52%</td>
<td>34.83%</td>
</tr>
<tr>
<td>Base 4 EV F</td>
<td>Daily Perfect Tracking</td>
<td>500</td>
<td>300</td>
<td>800</td>
<td>2,461.9</td>
<td>140.5</td>
<td>2.52%</td>
<td>46.26%</td>
</tr>
</tbody>
</table>

Key findings of this study include the following:
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 to capture all the curtailed renewable energy by EV charging in any of the 24 scenarios.

The maximum curtailed renewable energy can be captured under the Daily Perfect Tracking profile, 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 at some hours there is more demand for energy to charge EVs than is available through renewable resources.

The Type A EV charging profile (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.

For all charging profiles, EV charging scenarios, except Daily Perfect Tracking, increase both thermal generation and delivery of renewable generation (i.e., less curtailment) compared to the no EVA charging scenarios.

EV charging also increases CO2 emissions, fossil fuel consumption, and variable operating costs compared to the corresponding Base Cases. However, for a societal cost-benefit analysis, these impacts should be compared to the underlying costs and greenhouse gas emissions of equivalent fleets of conventional gasoline powered vehicles – an exercise that is beyond the scope of this project, and which also should include the associated costs and environmental impact of gasoline refining.

The greatest changes in system-level attributes, such as renewable curtailment, thermal generation, production costs, fuel consumptions, and emissions, occur in Base Case 2 related scenarios (300 MW Solar + 700 MW Wind). This case has the highest annual wind and solar energy available of all the scenarios studied.

Investigation of the seasonality of load and curtailed renewable energy indicates that:
Seasonal/monthly variations in hourly load patterns and diurnal curtailed energy patterns are very small, due to the fact that weather patterns in Oahu are nearly the same all year.

The lack of seasonality in Oahu load shape and curtailed renewable energy patterns implies that:

- An Annual Perfect Tracking (Type B) EV charging profile would come close to the Best We Can Do, or the Daily Perfect Tracking profile (Type F).

- There is no apparent reason to adjust EV charging schedules on a monthly or seasonal basis, since the average daily system load and renewable energy curtailment patterns are nearly the same for all months of the year.

The key findings of the electricity storage (ES) analysis are:

- Larger energy storage sizes:
  - Enable higher utilization of potential curtailed energy, and
  - Reduce the amount of additional thermal energy needed for EV Charging.

- Storage Charge Rate (measured in MW) can be kept as small as the maximum difference between the hourly curtailed energy and the hourly EV charging rate. A larger storage charging capacity will not be needed.

- Higher storage size (measured in MWh) will capture more of the curtailed energy for EV charging, but storage sizes need to be many times the size of daily EV charging in order to capture most of the curtailed energy. The reason is that there will be many periods when timing of curtailed energy and EV charging do not line up on together and the mount of the curtailed energy accumulates rapidly until EV charging starts to need the saved energy at times when there is curtailed energy.

The key findings of the spin requirement analysis are:

Normally all required spinning reserves are provided by baseload thermal generators. The study examined the possibility of providing a portion of the spinning reserves from alternate resources – such as demand response (DR) or battery energy storage systems (BESS) - thereby reducing the spinning reserves allocated to thermal generators. The results show that:

- Lowering the spinning reserves from baseload thermal generation results in reduction of curtailed energy in the No EV Base Cases and all of the EV Charging Profile scenarios.
Reducing spinning reserves from thermal generation by half results in more than a 10% reduction in curtailed energy in the examined Base Case 2 with more wind, and less than 10% reduction in curtailed energy in the examined Base Case 3 with more solar.
1 Introduction

1.1 Study Scope and Technical Approach

Environmental concerns, energy security, and higher fuel costs, or lack of reliable access to other sources of energy are the main drivers for the development of renewable energy for electricity production. However, in addition to their long-term societal, environmental, and economic benefits, higher penetration of renewable energy in the power grid also introduces some complications that impact power system operations. This study considers one such complication, which is the potential for some of the renewable energy to go unused (so-called curtailment or spillage of renewable energy) during periods of high electricity supply and low electricity demand. This impact is more accentuated in small and isolated systems such as Oahu’s power grid.

The Hawaii Natural Energy Institute engaged GE in support of the University of Hawaii’s Project “Hawaii Distributed Energy Resource Technology for Energy Security”, to perform a study of the impact of EV charging patterns on the Oahu power system and the reduction of the otherwise curtailed/spilled renewable energy during the times of high supply and/or low demand for electricity.

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. Fundamental modeling assumptions include:

- The solar generation consists of 60 MW central PV and 40 MW distributed PV.
- The wind generation consists of 100 MW on Oahu, 200 MW on Off-Island A and 200 MW on Off-Island B, which are connected to Oahu via an undersea electricity transmission cable.
- Oahu generation and load data are based on recent data from the Hawaii Solar Integration Study (HSIS).
- Oahu wind and solar generation resources are increased up to 1000 MW total, and operating reserve requirements were recalculated to cover the additional wind/solar variability.
In a separate section of the HREGP, this data will be reduced to determine the number of vehicles that will provide equivalent load and consumption profiles based on the following methodology.

- For comparison purposes, the Base Case will be simulated with 1000 MW wind/solar generation and no EVs.
- The total annual amount of curtailed renewable energy will be calculated in GWh. The project objective is to use as much of this energy as possible for charging EVs.
- The annual curtailed energy will be prorated (divided by 365 days) to determine the daily energy available for EV charging.
- Based on assumptions of vehicle types and driving patterns in Hawaii, the numbers of vehicles that can be served by the daily energy are presented in a subsequent section of this report. Determination of number of vehicles was not part of the scope of GE report.
- All off-island wind-generated electricity will be delivered to Oahu using an undersea transmission cable.

The study utilizes four additional “Cases”, each run as a base case using different combinations of additional wind and solar capacity, assuming no EV charging. These 4 Base Cases serve as benchmarks to measure the impact of different EV charging profiles and Scenarios. The four Base Cases are:

- Base Case 1: 500 MW of Wind + 100 MW of Solar
- Base Case 2: 700 MW of Wind + 300 MW of Solar
- Base Case 3: 500 MW of Wind + 500 MW of Solar
- Base Case 4: 500 MW of Wind + 300 MW of Solar

Layered over the four base cases are six basic EV charging profiles, examined for each Case are:

- 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 during each hour of day.
- Type C - Profile 1: 30% of daily charge during Day Period (8 AM to 5 PM, inclusive) and 70% of daily charge during Night Period (6 PM to 7 AM, inclusive).
- Type D – Profile 2: 30% of daily charge during On-Peak period (8 AM to 5 PM, inclusive), 0% of daily charge during the Critical Peak Period (6 PM to 9 PM, inclusive), and 70% of daily charge during Off-Peak period (10 PM to 7 AM, inclusive).

- Type E – Profile 3: 85% Evening Profile: 15% of daily charge during Day Period (8 AM to 5 PM, inclusive), 0% of daily charge during the Critical Peak Period (6 PM to 9 PM, inclusive), and 85% of the daily charge during the Night Period (10 PM to 7 AM, inclusive).

- Type F – Daily Perfect Tracking: Daily EV charging load shape proportional to that day’s curtailed energy load shape of the No EV Base Case.

GE analyzed 6 different profiles for each of the 4 Base Case, therefore the study covered 4 Base Cases and 24 Scenarios (total of 28 scenarios, since each base case had to be analyzed without any EV charging in order to calculate the resulting curtailed renewable energy). In addition GE performed the following three sensitivity analyses for each of the 24 scenarios:

- Different annual levels of EV charging.
- Integration of grid scale energy storage to supplant EV charging.
- Lower operating reserve requirements to reduce renewable energy curtailment.

1.2 Research Intent

The primary objectives of this study are to quantify the impact of different EV charging profiles on the operation of the Oahu electric power grid, and to investigate the effectiveness of an EV infrastructure to minimize curtailed renewable energy.

Different EV charging profiles considered in this study represent different control techniques that would manage EV charging profiles to further enhance the integration or wind and solar energy on the Oahu electric power grid by reducing renewable energy curtailment and/or providing a new source of reserves. This study focused on the first aspect of this objective, namely, impact on reduction of curtailed energy – although not on the regulatory and policy drivers, or incentives and pricing schemes that could foster and promote these EV charging profiles in the island.

The annual size of the EV electricity charging (the total GWh) was based on the unused portion of the renewable resources in the absence of the EV charging - the so called “dumped energy” or curtailed energy. The year 2015 was selected by HNEI to be the year to be modeled in this study.
The primary tools to quantify the impact on the grid of the various scenarios were a production cost simulation model and a spreadsheet-based model. GE’s Concorda Suite’s Multi-Area Production Simulation (GE-MAPS) model was used for the first four EV charging profiles to quantify operational performance over the course of a calendar year. The other last profiles were evaluated using the spreadsheet model.

The study used results of a statistical analysis which quantified variability in the wind and solar resources and determined the operating reserve requirements for the scenarios with more than 500 MW of wind and 100 MW of solar generation. The resulting hourly reserve requirements were input into the simulation.

System-wide attributes or performance measures to compare impact of different EC profiles included variable operating costs, dispatch/utilization for each generating unit, emissions, wind/solar curtailment, unserved load, etc.

Transmission system loading/utilization information is not necessary for this study, so the GE MAPS model assumed an unconstrained transmission system.

### 1.3 Impact of Higher Penetration of Renewable Energy

Integration of higher levels of renewable energy into the power grid has many long-term societal, environmental, and economic benefits, but also results in some adverse operational and economic impacts.

Although the overall impact of integration of renewable energy resources into the power grid is not the main focus of this study, one particular aspect of higher penetration of renewable energy provides the starting point for this work, which is the potential for curtailment (i.e., spilling) of unneeded renewable energy. One result of higher penetration of renewable energy (wind and solar) into the grid is the higher incidence of oversupply of electric energy during low electricity demand periods. The likelihood of high levels of renewable energy curtailment is higher in isolated and smaller electric power systems such as Oahu’s. Curtailment of wind and solar energy may occur during periods of high supply and/or low electricity demand, and is accentuated in the case of wind power, since wind generation occurs throughout the day, in contrast to solar power, which occurs mainly during peak demand periods.

Since renewable energy’s fuel is abundant at almost no variable cost (i.e., fuel sources being the wind and the sun), it is more valuable than the electric energy from thermal generation sources (e.g., coal, natural gas, fuel oil). Hence, during times of high supply and low demand, all attempt is made to ramp down un-needed thermal generation. This ramping down of thermal generation, however, has a limit. For instance, committed thermal units
cannot be ramped down below their operational minimum load. Furthermore, some thermal units are “must-run” units, which are necessary to maintain grid reliability.

In such situations when all opportunities for reducing thermal energy have been exhausted, the only remaining way to reduce electrical power is curtail renewable resources, thereby spilling the surplus energy.

This study quantifies the curtailed/spilled renewable energy without any EV charging for four Base Cases that represent different penetration levels of wind and solar energy.

This study also quantifies the curtailed energy that can be captured under the six different EV charging patterns for each of the four Base Cases.

### 1.4 Application of Demand Side Approach and Energy Storage

For most of the history of electric power system, the main approach to balancing the electric supply and demand has been based on reliance on supply side resources such as fast acting hydro plants and agile thermal peaking units. In more recent years, demand side resources have started to play a larger role in energy, capacity, and ancillary services markets.

Demand Management or Demand Response (DR) covers the whole range of demand side resources from direct load control (operators disconnect load on demand) to responsive demand based on dynamic pricing and other control signals (price schedules or signals are passed to customers to incent load reduction). The advent of new technology is enabling more sophisticated and engaging demand response options that, coupled with dynamic pricing, are making possible more flexible and robust customer response behavior. Smart Grid innovations in advanced metering infrastructure (AMI), communications, and home energy management systems are making DR both technologically feasible and economically viable and are enabling wide deployment.

Despite the relatively slow economy, utility and retail DR programs are being driven by state regulatory commissions and by utilities in need of managing their peak demand and reducing long-term capacity costs. Furthermore, more recent FERC orders on “Demand Response Compensation in Organized Wholesale Markets” are expected to open up opportunities for participation by demand resources in the electricity wholesale markets

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operated by Independent System Operators (ISOs) such as ISO-NE, NYISO, CAISO, and others; with a DR resource to be paid the hourly locational marginal price (LMP), and to be treated similarly to supply side resources in the energy, capacity, and ancillary services markets.

There are four general types of time-varying dynamic pricing structures (also referred to as time-differentiated rates or tariffs):

- **Time of Use (TOU) Pricing**: TOU pricing provides two different electricity rates for on-peak and off-peak periods – utilities and customers benefit by lowering on-peak demand, or shifting demand from on-peak periods to off-peak periods.

- **Critical Peak Pricing (CPP)**: CPP, in addition to an underlying TOU rates, include, with advanced notification, a very high price during a few critical peak periods during the year.

- **Critical Peak Rebate (CPR)**, also called Peak Time Rebate (PTR): which is similar to CPP in some ways with the major difference being that instead of a high price, customers are given a rebate if they reduce their demand from a pre-determined base line.

- **Real Time Pricing (RTP)**: Is the most complex and provides the most economically based pricing signal reflecting the hour by hour cost of electricity service, where prices change by the hour, typically provided a day in advance. RTP is suitable for more advanced or technically savvy customers.

Although the application of these methods and programs to deal with incidents of high renewable energy curtailment could be presumed to be limited - since these programs are mostly intended to curtail demand for electricity, whereas, what is needed is increased demand for electricity – some variations to these DR programs and Dynamic Pricing rates can be employed to influence the EV charging behavior. For instance:

- **TOU rates can be designed**: to have high prices during low supply and high demand periods to discourage EV charging, and to have low prices during high supply and low demand periods (likely periods for high renewable energy curtailment) to encourage EV charging. Design of the TOU rate and timing of the periods requires a study similar to the one performed for this project, albeit in more detail and with consideration of probabilistic solar, wind, and load hourly patterns, in order to account of a wide range of possibilities.

- **A “reverse-CPP” rate can be designed** to send a day-ahead low price to hold for the periods of expected high curtailment, to signal a good time for EV charging (among other electricity consuming activities),
A “reverse-CPR/PTR” rate can be designed to also provide a day-ahead notice of rebate for higher demand during the periods of expected high curtailment, also to signal a good time for EV charging.

RTP hourly prices can drop very low during high supply periods, providing incentive for increased electricity usage and timing of EV charging. In addition large industrial, commercial, and agricultural customers can shift high electricity usage periods to low price times that could coincide with high renewable energy supply periods.

It should be noted that design of appropriate rates and incentives to influence smart EV charging schedules is not within the scope of this project. However, proper design of the rates and incentives should significantly influence the timing of EV charging.

### 1.5 Role of Energy Storage

Another potential resource that can be utilized to deal with higher electricity supply and prevent additional curtailment is the energy storage, which comes in variety of types and sizes.

Energy Storage provides the means for electricity load shifting from on-peak periods (characterized by higher electricity prices, higher electricity demand, and lower operating reserve margins) to off-periods (characterized by lower electricity prices, lower electricity demand, and higher operating reserve margins).

Energy Storage (ES) Systems are expected to play a larger role in the future grid. There are a wide variety of ES systems, depending on the technology and also depending on their functionality. The major storage types include:

- Battery Energy Storage Systems (BESS)
- Thermal Energy Storage Systems - Heat and Cool (TESS)
- Building Thermal Mass
- Pumped Hydro Storage
- Compressed Air Energy Storage (CAES)
- Flywheel
- Ultra Capacitors
- Superconducting Magnetic Energy Storage (SMES)

The appropriate technology would depend on the intended application. For instance, storage of energy is best accomplished by high energy (kWh) (i.e., storage size in terms of
volume) and low power (kW) (i.e., storage size in terms of charge and discharge rate) characteristics. On the other hand, fast response requirements are best met by energy systems with low energy and high power characteristics.

For purposes of capturing potentially curtailed renewable energy, grid scale energy storage seems most appropriate. These include Pumped Hydro Storage, CAES, TESS, and packaged banks of BESS. Such grid scale energy storage can be charged with electricity during the high supply times (times of potential curtailment of renewable energy) and then discharged at later times during high demand periods when electricity supply on the grid is low.

In a later section of this report we consider the role of energy storage in conjunction with EV charging and its impact on reducing the renewable energy curtailment.

### 1.6 Modeling of the Oahu Power System

As described in the next chapter, the production simulation analysis of the Oahu power system was performed using GE’s proprietary Concorda Suite’s Multi-Area Production Simulation (GE MAPS) software in order to evaluate hour-by-hour grid operation of each scenario with different wind and load profiles. The production simulation results quantified numerous impacts on grid operation including system-wide thermal and renewable electric generation, curtailed renewable energy, fossil fuel consumption, environmental emissions, and variable operating costs.

We also used a spreadsheet model to measure the potential reduction in curtailed energy of varying the EV fleet size, EV charging profiles, and energy storage capacity.

### 1.7 Research Approach

Our main approach to determine EV charging profiles, or schedules, was to extrapolate limited Oahu driving survey data into EV charging behavioral preferences, and then using the resulting hourly increases in electricity demand to modify the system’s assumed hourly electric load.

We 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.

As described in the next chapter, we considered a number of EV charging profiles (basically different hourly load shapes), both to demonstrate the impact of different EV charging schedules and to bookend” the analysis by quantifying the best and worst possible
outcomes based on the most simple (i.e., uniform) EV schedule and the most complex (i.e., daily perfect tracking) schedule. The realistic outcomes for EV charging schedules, driven by future regulatory policies and incentive and pricing programs, would be somewhere between these very simple and very complex profiles.

We based our analysis on deterministic EV schedules and did not consider probabilistic behavior or perform any stochastic analyses. That could be the subject of future research. Our 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 and ES capacities, to help policy makers design appropriate incentive and pricing programs that would best achieve higher utilization of renewable resources on Oahu.
2 Modeling Approach

To determine the impact of different EV charging patterns on the curtailment of renewable energy on Oahu, we used two different, but complementary, types of analysis:

- Hourly production costing simulation of the Oahu power system using GE MAPS, and
- Spreadsheet-analysis of EV charging demand for renewable and conventional power resources.

The first type of analysis provided insight into hourly operations of the Oahu power system, quantified the amount of potentially curtailed (i.e., spilled) renewable energy, and enabled the calculation power system operational results based on the EV charging load profile, including changes in system-wide variable operating costs, fuel consumption, and environmental emissions.

The second type of analysis enabled quantification of the amount of renewable versus fossil-fuel based electricity used by the EV charging load under different EV charge patterns, considering various EV fleet sizes, and utilizing different grid-scale energy storage sizes.

GE’s Concorda Software Suite’s Multi-Area Production Simulation (GE MAPS) model, which is a chronological hourly security constrained unit commitment and economic dispatch (SCUC/ED) model, was used to simulate the hourly operation of the Oahu system for a single study year using generator production cost data and the regulation and load-following requirements identified in the statistical analysis. “Chronological: in this context means that the model considered hours of operations in a sequential manner, in contrast to some other production costing models that only consider the level of hourly load from high to low (i.e., Load Duration Curve), with no consideration of the time chronology. “Security Constrained” in this context means that the model takes into account the transmission constraints in the system that should be considered for the secure operation of the power system. The model’s scheduling of generation does not violate the modeled transmission constraints, including the thermal limits of the lines and the system contingency limits (limits on power flows in lines needed to provide reserve capacity if other lines or power sources in the grid are tripped).

The transmission impacts were not taken into account since transmission issues were not within the scope of study and hence, particularly since EV charging load was assumed to be dispersed within the grid without consideration for locational issues.

GE MAPS has been continuously developed, refined and benchmarked for over 30 plus years and has been applied to system economic analyses of interconnected power grids of
U.S., Canada, and a few other countries. Additional information about GE MAPS is provided in the Appendix.

The GE MAPS production simulations employed in this study were conducted chronologically in one-hour time steps. Consequently, the sub-hourly real-time adjustments of generation to compensate for variations in balancing area net demand were not modeled explicitly. Instead, the responsive generation that would be necessary in a given hour to regulate and balance the system was represented as constraints on the unit commitment and economic dispatch algorithms in the production model. The determination of the appropriate constraints that reflect the additional variability and short-term uncertainty introduced by wind generation was the objective of the statistical analysis which was performed prior to the running the model. Those “operating rules”, which used current hour values of load and wind generation along with forecasts of those quantities, were entered into the model as reserve constraints for each hour of the production simulation. The commitment, dispatch and cost implications of those reserves were quantified in the GE MAPS results.

The simulation outputs include, but are not limited to, the following.

- Annual production cost (variable operating cost)
- Zonal and Locational Marginal Prices (LMPs)
- Changes in emissions (NOx, SO2, and CO2)
- Undelivered (i.e., curtailed or spilled) renewable energy
- Demand response deployed and load not served
- Unit performance
- Starts, online hours, peaking unit utilization, cycling, etc.

### 2.1 Modeling Assumptions

Modeling is based on the following fundamental assumptions:

- The solar generation includes 60 MW central PV and 40 MW distributed PV.
- The wind generation includes 100 MW on Oahu as well as 200 MW on Off-Island A and 200 MW on Off-Island B, which would be connected to Oahu via HVDC transmission.
- Oahu thermal generation data are based on data from the ongoing HSIS.
- Oahu load data are based on recent data from the ongoing HSIS.
- Oahu fuel price projections are based on recent data from the ongoing HSIS.
Oahu wind and solar generation resources are increased up to 1000 MW total, and operating reserve requirements were recalculated to cover the additional wind/solar variability.

- Hourly operating reserve requirements are based on the statistical analysis of wind, solar, and load data using the same methodologies as the OWITS and HSIS studies used. Hourly operating reserve requirements were calculated for each combination of wind and solar mix (the 4 base cases in the study) and vary with each hour depending on the wind, solar, and load patterns for a given case. These hourly operating reserve requirements are directly input into the GE MAPS model. The model performs unit commitment and economic dispatch while maintaining the given hourly operating reserves requirements.

2.2 Base Cases

In order to allow comparing of impacts across scenarios, the study assumed that the Base Case annual size of the EV electricity charging (the total GWh) is based on the unused portion of the renewable resources in the absence of the EV charging – i.e., the curtailed/spilled energy. All the simulations were done for the 2015 load year.

The following table presents the combination of renewable resources to be included in the Base cases.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Oahu Central Solar</th>
<th>Oahu Distributed Solar</th>
<th>Oahu Wind</th>
<th>Off-Island Wind A</th>
<th>Off-Island Wind B</th>
<th>Total Wind</th>
<th>Total Solar</th>
<th>Total Wind + Solar</th>
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<td>40</td>
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<td>200</td>
<td>200</td>
<td>500</td>
<td>300</td>
<td>800</td>
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</tbody>
</table>

The “Original Database” is derived from the Stage 2 Oahu-Maui Interconnection Study. The Original Database includes 300 MW of Wind (the “Original Wind”):
- 100 MW of wind on Oahu
  - A 30 MW plant
  - A 70 MW plant
- 200 MW plant on Off-Island A dedicated to deliver power to Oahu

The Original Database includes 100 MW of Solar (the “Original Solar”):
- 40 MW of Central Solar on Oahu (multiple plants)
- 60 MW of Distributed Solar on Oahu

The Base Cases 1 to 4 are based on installing additional wind and solar resources over the Original Database according to the following plan.

- **Base Case 1 (600 MW: 500 MW Wind + 100 MW Solar):**
  - 300 MW Original Wind
  - 100 MW Original Solar
  - 200 MW new Wind on Off-Island B dedicated to deliver power to Oahu

- **Base Case 2 (1000 MW: 700 MW Wind + 300 MW Solar):**
  - 300 MW Original Wind
  - 100 MW Original Solar
  - 200 MW new Wind on Off-Island B dedicated to deliver power to Oahu
  - 200 MW new Wind on Oahu
  - 100 MW new Central Solar plant on Oahu
  - 100 MW new Distributed Solar on Oahu in same distributed locations as Original Solar

- **Base Case 3 (1000 MW: 500 MW Wind + 500 MW Solar):**
  - 300 MW Original Wind
  - 100 MW Original Solar
  - 200 MW new Wind on Off-Island B dedicated to deliver power to Oahu
  - 200 MW new Central Solar on Oahu (2 x 100 MW plants)
  - 200 MW new Distributed Solar on Oahu in same distributed locations as Original Solar

- **Base Case 4 (800 MW: 500 MW Wind + 300 MW Solar):**
  - 300 MW Original Wind
100 MW Original Solar
200 MW new Wind on Off-Island B dedicated to deliver power to Oahu.
100 MW new Central Solar plant on Oahu
100 MW new Distributed Solar on Oahu, same locations as in original distributed solar

2.3 Scenarios based on EV Charging Profiles

The scope of work includes analysis of 4 base cases with no EV charging and 6 scenarios of different EV charging profiles for each base case. The 4 base cases and first 4 of the EV profiles for each base case – a total of 20 cases- were simulated using the GE MAPS production cost model. The last two profiles for each base case were evaluated using spreadsheet analysis using the GE MSPS outputs for the original base cases.

A scenario is a predominantly defined by a combination of wind/solar generation, vehicle charging requirement (MWh), and charging profile. The first 4 EV charging profiles were defined at the beginning of the project. The last two were defined later after reviewing preliminary results from the first set of scenarios.

In addition to the main scenarios, additional sensitivity cases were considered, including:

- Variation in the EV fleet size (e.g., Smaller: 50% of the base fleet, or Larger: 200% of the base fleet),
- Addition of energy storage of various sizes to the power grid, and
- Lowering required operating reserves.

2.4 EV Charging Profiles

We developed six EV charging profiles:

- Type A - Annual Uniform Charging:
  - Uniform EV Charging every hour of the year set at the Hourly Average of the Annual Curtailed Renewable Energy of the corresponding Base Case, i.e., Annual Curtailed Energy divided by 8760 hours. See Figure 1.
  - This profile, although unrealistic, provides a worst case scenario, to help set the low end of the potential curtailment reduction.

- Type B - Annual Perfect Tracking:
○ EV Charging at each hour of the day set at the Annual Average of Curtailed Energy at that hour of the day, i.e., EV charging at hour X is the same for every hour X in the year. See Figure 3.

○ Although also unrealistic, this profile is assumed to be one of the most effective in reducing the renewable curtailment.

> Type C - Annual Profile 1:

○ 30% of Daily Charging during Day Period (7am – 5pm), 70% during Evening Period (5pm – 7am). See Figure 6.

○ Uniform hourly charge within each period, with ramp ups and ramp downs between periods.

○ This profile can be assumed to represent a reasonable EV charging schedule – for instance, a profile that comes into place as a result of EV owners’ response to a two-tier TOU tariff.

> Type D - Annual Profile 2:

○ 30% of Daily Charging during Day Period (7am – 5pm), 0% during Peak Period (5pm – 9pm), and 70% during Evening Period (9pm – 7am). See Figure 7.

○ Uniform hourly charge within each period, with ramp ups and ramp downs between periods.

○ This profile is assumed to reasonably represent a reasonable EV charging schedule – for instance, a profile that comes into place as a result of EV owners’ response to a three-tier TOU tariff, reverse-CPP rates, or reverse-PTR rates.

> Type E - Annual 85% Evening Profile:

○ 15% Daily Charging during Day Period (7am – 5pm), 0% during Peak Period (5pm – 9pm), and 85% during Evening Period (9pm – 7am). See Figure 8.

○ Uniform hourly charge within each period, with ramp ups and ramp downs between periods.

○ This profile is also a reasonable representation of TOU schedules. The project team selected this profile as an example of a realistic choice.

> Type F - Daily Perfect Tracking:

○ EV Charging pattern during the day is proportional to the Daily Curtailed Energy Shape (but total Daily EV Charging energy is fixed).
If there is no Curtailed Energy during a day, the default profile is Uniform Charging for that day.

Although this profile is very unrealistic, requiring the greatest degree of control on the behavior of EV owners and timing of their EV charging, it nevertheless provides “The Best We Can Do” EV charging schedule, and as such, provides a best-case scenario to help set the high end of the potential curtailment reduction.

The following figures illustrate the hourly EV charging patterns under the first five profiles. Each of the 4 base cases have the same profiles of EV charging for Types A, C, D, and E, since the proportionality of the hourly EV charge to the total daily EV charge under these profiles does not depend on the underlying base case. However, the profile of the Type B EV charging depends on the hourly shape of the underlying base case. Hence, separate Type B charts are provided for each case. Same is true for Type F EV charging, i.e., Daily Perfect Tracking, where the daily EV charging pattern is different for each base case, it only changes daily within each base case.

![Figure 1: Hourly Pattern of Type A EV Charging (Annual Uniform Profile)](image)
Figure 2: Hourly Pattern of Type B EV Charging (Annual Perfect Tracking) for Base Case 1

Figure 3: Hourly Pattern of Type B EV Charging (Annual Perfect Tracking) for Base Case 2
Figure 4: Hourly Pattern of Type B EV Charging (Annual Perfect Tracking) for Base Case 3

Figure 5: Hourly Pattern of Type B EV Charging (Annual Perfect Tracking) for Base Case 4
Figure 6: Hourly Pattern of Type C EV Charging (Profile 1)

Figure 7: Hourly Pattern of Type D EV Charging (Profile 2)
2.4.1 EV Charging Principal Assumptions

To enable comparison and benchmarking across the scenarios, the following EV charging assumptions were made.

- Unless specified, the total annual amount of electricity used to charge the EV Fleet is assumed to be equal to the total curtailed renewable energy in the corresponding Base Case. This assumption enables comparisons across scenarios. More specifically:
  - EV charging in Case 1 based Scenarios = 209,791 MWh/Year
  - EV charging in Case 2 based Scenarios = 735,662 MWh/Year
  - EV charging in Case 3 based Scenarios = 400,653 MWh/Year
  - EV charging in Case 4 based Scenarios = 261,525 MWh/Year

- Daily EV Charging is the same every day, which implies that for a given EV fleet, the drivers’ total daily electricity needs do not change from day to day. More specifically:
  - EV charging in Case 1 based Scenarios: 574.77 MWh/Day
o EV charging in Case 2 based Scenarios = 2015.51 MWh/Day
o EV charging in Case 3 based Scenarios = 1097.68 MWh/Day
o EV charging in Case 1 based Scenarios: 716.51 MWh/Day

The next chapter provides the key findings of the study and results for each Base Case and EV charging scenario. It also describes a number of other scenarios and sensitivity analyses performed to gauge the impact on renewable curtailment, namely:

- Different quantities of EV’s in the fleet (50% and 200% of assumed EV charging load),
- Various sizes of storage to further reduce renewable curtailment, and
- Lower operating reserve requirements.
3 Key Findings

3.1 Classification of Modeling Results

The analysis performed in this project provided a number of different types of results, which include, but are not limited to:

- Amount of renewable energy curtailment under the Base Cases (no EV Charging) and Scenario Cases (different EV charging profiles),
- Impact of different EV charging profiles on power system operational and economic performance, such as system-wide variable operational costs, fossil fuel consumption, and greenhouse gas (i.e., CO2) emissions,
- Impact of varying sizes of EV fleet on renewable energy curtailment.
- Impact of energy storage of different sizes on renewable energy curtailment.
- Impact of changing the operational reserve requirements on renewable energy curtailments.

As a reminder, the four Base Cases are shown here again in Table 3.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Oahu Central Solar</th>
<th>Oahu Distributed Solar</th>
<th>Oahu Wind</th>
<th>Off-Island Wind A</th>
<th>Off-Island Wind B</th>
<th>Total Wind</th>
<th>Total Solar</th>
<th>Total Wind + Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1</td>
<td>40</td>
<td>60</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>500</td>
<td>100</td>
<td>600</td>
</tr>
<tr>
<td>Base 2</td>
<td>140</td>
<td>160</td>
<td>300</td>
<td>200</td>
<td>200</td>
<td>700</td>
<td>300</td>
<td>1000</td>
</tr>
<tr>
<td>Base 3</td>
<td>240</td>
<td>260</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>500</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Base 4</td>
<td>140</td>
<td>160</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>500</td>
<td>300</td>
<td>800</td>
</tr>
</tbody>
</table>

The following sections will describe each type of result.
3.2 Renewable Energy Curtailment in Four Base Cases

The first step in modeling the Oahu power system was to quantify the amount of curtailed, i.e., spilled, renewable energy under the business-as-usual load projection, i.e., in the absence of any EV charging, under four different solar and wind power scenarios. This was accomplished by hourly simulation of the Oahu power system using GE MAPS models for each of the four solar and wind combinations (Base Cases 1 to 4), with no EV charging to determine the hourly curtailed renewable energy.

The curtailment of renewable energy occurs at times of high supply and low demand. Reliable operation of the electric power system requires instantaneous matching of electricity supply and demand. At times when there is surplus supply in the system, steps must be taken to reduce the electricity supply by decreasing power generation. Given that renewable energy has almost zero fuel costs, and hence is the most valuable instantaneous resource, it is the last resource that would be curtailed in such situations, after all other choices, including reduction in thermal unit generation, have been exhausted.

There are limits to how much thermal generation can be reduced, short of shutting down the plants. From a technical standpoint, loading of thermal generation can be reduced down to the minimum operational capacity. In this analysis we are ignoring the sub-hourly operations which would require consideration of unit ramp rates that determine how fast thermal generation load can be reduced. In our hourly analysis, we assume that thermal generation ramp rates are high enough to enable ramping thermal generation units down to their minimum capacity if need be. Furthermore, those thermal units which are designated as must-run will continue to operate, since they are needed for reliable operation of the system. Only after all other thermal generation options have been exhausted, and the system is still experiencing surplus generation, would renewable energy be curtailed. The curtailment of renewable energy plants would be based on a priority order set by the operator. We have designated a priority list in the GE MAPS modeling, which is simply based on last installed, first curtailed criteria.

The GE MAPS analysis determined the hourly curtailed renewable energy, by type, for each of the four Base Cases. Results are shown in Table 4. Other than different levels of solar and wind power mix in the system, all other system attributes are the same across all four cases.

Although Base Case 2 and Base Case 3 both have 1000 MW of renewable energy, the amount of curtailed renewable energy is higher in Base Case 2, since this case has more wind energy, which has more off-peak period generation compared to solar energy. In Base Cases 1, 3, and 4 which all have the same amount of wind energy, the renewable curtailment is higher for cases with more solar power.
### Table 4: Available and Curtailed Renewable Energy under for each of the 4 Base Cases

<table>
<thead>
<tr>
<th>Base Cases</th>
<th>Wind (MW)</th>
<th>Solar (MW)</th>
<th>Total (MW)</th>
<th>Unit</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>
</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>
</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>
</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>
</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>
</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>
</tr>
<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>
</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>
</tr>
<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>
</tr>
</tbody>
</table>

### 3.3 Energy Curtailed Under Different EV Charging Profiles

The next step was to quantify the impact on the renewable energy curtailments of the different EV charging profiles due to the additional demand for electricity brought about by the EV charging loads.

Our EV charging assumptions - namely, (1) annual EV charging being equal to the total Base Case curtailed renewable energy, and (2) daily EV charging amount and hourly patterns remain the same from day to day - are bound to result in many time periods when hourly EV Charging is either above or below the hourly Curtailed Energy. The Delta can be either positive or negative.

Table 5 summarizes the simulation results for all the Base Cases and the EV charging scenarios.
<table>
<thead>
<tr>
<th>Scenarios</th>
<th>EV Profile</th>
<th>Available Solar/Wind Total (GWh)</th>
<th>Curtailment Solar/Wind As % Of Total From the Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1 No EV</td>
<td>No EV</td>
<td>2,105.9</td>
<td>9.96%</td>
</tr>
<tr>
<td>Base 1 EV A</td>
<td>Annual Uniform Charging</td>
<td>2,105.9</td>
<td>8.07%</td>
</tr>
<tr>
<td>Base 1 EV B</td>
<td>Annual Perfect Tracking</td>
<td>2,105.9</td>
<td>6.11%</td>
</tr>
<tr>
<td>Base 1 EV C</td>
<td>Annual Profile 1</td>
<td>2,105.9</td>
<td>7.82%</td>
</tr>
<tr>
<td>Base 1 EV D</td>
<td>Annual Profile 2</td>
<td>2,105.9</td>
<td>6.99%</td>
</tr>
<tr>
<td>Base 1 EV E</td>
<td>85% Evening Profile</td>
<td>2,105.9</td>
<td>6.56%</td>
</tr>
<tr>
<td>Base 1 EV F</td>
<td>Daily Perfect Tracking</td>
<td>2,105.9</td>
<td>5.31%</td>
</tr>
<tr>
<td>Base 2 No EV</td>
<td>No EV</td>
<td>3,178.1</td>
<td>23.15%</td>
</tr>
<tr>
<td>Base 2 EV A</td>
<td>Annual Uniform Charging</td>
<td>3,178.1</td>
<td>13.85%</td>
</tr>
<tr>
<td>Base 2 EV B</td>
<td>Annual Perfect Tracking</td>
<td>3,178.1</td>
<td>12.57%</td>
</tr>
<tr>
<td>Base 2 EV C</td>
<td>Annual Profile 1</td>
<td>3,178.1</td>
<td>13.89%</td>
</tr>
<tr>
<td>Base 2 EV D</td>
<td>Annual Profile 2</td>
<td>3,178.1</td>
<td>12.63%</td>
</tr>
<tr>
<td>Base 2 EV E</td>
<td>85% Evening Profile</td>
<td>3,178.1</td>
<td>12.79%</td>
</tr>
<tr>
<td>Base 2 EV F</td>
<td>Daily Perfect Tracking</td>
<td>3,178.1</td>
<td>10.80%</td>
</tr>
<tr>
<td>Base 3 No EV</td>
<td>No EV</td>
<td>2,817.9</td>
<td>14.22%</td>
</tr>
<tr>
<td>Base 3 EV A</td>
<td>Annual Uniform Charging</td>
<td>2,817.9</td>
<td>9.79%</td>
</tr>
<tr>
<td>Base 3 EV B</td>
<td>Annual Perfect Tracking</td>
<td>2,817.9</td>
<td>8.51%</td>
</tr>
<tr>
<td>Base 3 EV C</td>
<td>Annual Profile 1</td>
<td>2,817.9</td>
<td>9.97%</td>
</tr>
<tr>
<td>Base 3 EV D</td>
<td>Annual Profile 2</td>
<td>2,817.9</td>
<td>9.13%</td>
</tr>
<tr>
<td>Base 3 EV E</td>
<td>85% Evening Profile</td>
<td>2,817.9</td>
<td>9.36%</td>
</tr>
<tr>
<td>Base 3 EV F</td>
<td>Daily Perfect Tracking</td>
<td>2,817.9</td>
<td>7.16%</td>
</tr>
<tr>
<td>Base 4 No EV</td>
<td>No EV</td>
<td>2,461.9</td>
<td>2.64%</td>
</tr>
<tr>
<td>Base 4 EV A</td>
<td>Annual Uniform Charging</td>
<td>2,461.9</td>
<td>2.48%</td>
</tr>
<tr>
<td>Base 4 EV B</td>
<td>Annual Perfect Tracking</td>
<td>2,461.9</td>
<td>2.48%</td>
</tr>
<tr>
<td>Base 4 EV C</td>
<td>Annual Profile 1</td>
<td>2,461.9</td>
<td>2.52%</td>
</tr>
<tr>
<td>Base 4 EV D</td>
<td>Annual Profile 2</td>
<td>2,461.9</td>
<td>2.52%</td>
</tr>
<tr>
<td>Base 4 EV E</td>
<td>85% Evening Profile</td>
<td>2,461.9</td>
<td>2.52%</td>
</tr>
<tr>
<td>Base 4 EV F</td>
<td>Daily Perfect Tracking</td>
<td>2,461.9</td>
<td>2.52%</td>
</tr>
</tbody>
</table>

We can readily observe that the lowest level of curtailment (or highest level of avoided curtailment) occurs under the Type B or Annual Perfect Tracking EV Charging scenarios.
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, the least capable in capturing the potentially curtailed renewable energy.

In Case 1 related scenarios the highest level of reduction in curtailed renewable energy from the Base Case level 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 29.81% reduction. Comparable reductions are 55.35% and 45.43% for Case 2 related scenarios, 49.63% and 35.83% for Case 3 related scenarios, and 46.26% and 32.88% for Case 4 related scenarios.

Figure 9 through Figure 12 show the relative renewable energy curtailment under each EV charging scenario relative to the curtailment under the corresponding Base Case.
Figure 9: Renewable Energy Curtailment in Base 1 EV Charging Scenarios

Figure 10: Renewable Energy Curtailment in Base 2 EV Charging Scenarios
Figure 11: Renewable Energy Curtailment in Base 3 EV Charging Scenarios

Figure 12: Renewable Energy Curtailment in Base 4 EV Charging Scenarios
3.4 The Best EV Charging Profile: Limits to Capture of Curtailed EV Charging

In this section we address the question of what is the Best We Can Do in terms of an EV charging profile that captures most of the potentially curtailed energy.

The Best We Can Do profile is the Daily Perfect Tracking. The profile assumes that every day, 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.

The following sections consider three levels of annual EV charging:

1. 100% EV Charging: The scenario where the total annual EV charging equal to the total annual curtailed renewable energy. This is the base annual EV charging level that has been considered so far.

2. 50% EV Charging: The scenario where the total annual EV charging is half the total annual curtailed renewable energy.

3. 200% EV Charging: The scenario where the total annual EV charging is twice the total annual curtailed renewable energy.

In those other cases, it is again assumed that the total daily EV charges will stay the same from day to day.

The limit to capturing potentially curtailed renewable energy for the 100% EV Charging for the Base Case 2 is demonstrated in Figure 13.
The 100% EV Charge line is valid for all EV Charging profile types under Base Case 2, since although the hourly charging is different under different profiles, the total daily charging does not depend on the profile type.

The scatter plot clearly indicates that there are many days in which the amount of curtailed energy is above the total daily EV charging possible under our assumptions of fixed daily EV charging. There are also many days when the curtailed energy is lower than the total daily EV charging level, although this does not mean that on an hourly basis, all curtailed energy can be captured by EV charging, since most of the profiles studied here, assume that the daily EV charging pattern does not change from day to day, whereas the hourly curtailed energy changes from hour to hour.

Figure 14 presents the same information, except that the daily curtailed energy is represented by a sorted duration curve instead of a chronological scatter plot – i.e., instead of plotting daily curtailed energy sequentially for each day throughout the year, the daily curtailed energy is plotted starting at left with the day with the highest daily curtailed energy and moving down and ending with the day with the lowest daily curtailed energy on the right.
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 EV charging schedule is expected to increase thermal energy generation compared to the corresponding No EV Base Case.
3.5 Impact of Varying the Number of EV’s on the Grid

We next considered other EV Charging Cases:

- 50% EV Charging Case: Total Annual EV Charging Level is at 50% of the Total Annual Curtailed Energy
- 200% EV Charging Case: Total Annual EV Charging Level is at 200% of the Total Annual Curtailed Energy.

As shown in the following figure, in an annual EV charging level at 50% of the annual curtailed energy, the EV charging level (Red Line) moves down, this implies that more of the curtailed energy goes unused.

In contrast, as shown in the following figure, in an annual EV charging level at 200% of the annual curtailed energy, the EV charging level (Red Line) moves up, this implies that more of the curtailed energy gets captured. However, the higher EV Charging level also requires more Thermal Energy (the area below Red Line but above Blue Curve).
A similar duration curve representation can be constructed for the 85% EV charging profile, as shown in Figure 17. This representation requires hourly (in contrast to daily) values, in order to segment the curtailed energy duration curves into the Evening (Night), Day, and Peak periods. The chart shows the proportion of the curtailed energy that can be captured in each of these daily sub-periods.
Figure 17: Duration Curve for Curtained Energy under Type E EV Charging Profile

Note that although we are assuming that 85% of the total daily EV Charging will occur during the two Evening Periods, as shown in Table 6, on average only about 48% of the total daily Curtained Energy occurs during Evening Periods.

<table>
<thead>
<tr>
<th>Period of Day</th>
<th>Curtained Energy (MWh)</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day Curtailed (7am - 5pm)</td>
<td>792</td>
<td>39.3%</td>
</tr>
<tr>
<td>Peak Curtailed (5pm - 9pm)</td>
<td>83</td>
<td>4.1%</td>
</tr>
<tr>
<td>Evening Curtailed (9pm - 7am)</td>
<td>1,141</td>
<td>56.6%</td>
</tr>
<tr>
<td>Total Daily Curtailment</td>
<td>2,016</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 7 through Table 14 present the results for 50%, 100%, and 200% EV Charging levels for all four Base Cases and the following two profiles:

- EV Charging Type D: Profile 2 (Daily Charging: 70% in Evening Period, 30% in Day Periods, 0% in Peak Period, with Ramp-Ups and Ramp-Downs between periods)

- EV Charging Type Daily E: Perfect Tracking Profile (“The Best We Can Do”)
Profile 2 was selected, since it is representative of a more realistic EV charging profile - compared to the others examined in this study - that can be implemented by the policy makers. Daily Perfect Tracking profile, which is the Best We Can Do, was included for comparison.

Table 7: Performance of Differently Sized EV Fleets in Base Case 1 under Type D EV Charging (Profile 2)

<table>
<thead>
<tr>
<th>Base Case 1 EV Charging Type D</th>
<th>Units</th>
<th>EV Charging From Renewable Energy</th>
<th>EV Charging From Thermal Energy</th>
<th>Total EV Charging Energy</th>
<th>Unused Curtained Energy</th>
<th>Used Curtained Energy</th>
<th>Total Curtained Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% EV Charging (GWh)</td>
<td>33</td>
<td>72</td>
<td>105</td>
<td></td>
<td>177</td>
<td>33</td>
<td>210</td>
</tr>
<tr>
<td>100% EV Charging (GWh)</td>
<td>63</td>
<td>147</td>
<td>210</td>
<td></td>
<td>147</td>
<td>63</td>
<td>210</td>
</tr>
<tr>
<td>200% EV Charging (GWh)</td>
<td>111</td>
<td>308</td>
<td>420</td>
<td></td>
<td>99</td>
<td>111</td>
<td>210</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Base Case 1 EV Charging Type D</th>
<th>% of Total</th>
<th>Energy Usage</th>
<th>Energy Usage</th>
<th>Total Energy Usage</th>
<th>Curtained Energy</th>
<th>Curtained Energy</th>
<th>Curtained Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% EV Charging</td>
<td>31.6%</td>
<td>54.8%</td>
<td>45.2%</td>
<td>100.0%</td>
<td>72.6%</td>
<td>27.4%</td>
<td>100.0%</td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>29.8%</td>
<td>46.7%</td>
<td>53.3%</td>
<td>100.0%</td>
<td>53.3%</td>
<td>46.7%</td>
<td>100.0%</td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>26.5%</td>
<td>35.9%</td>
<td>64.1%</td>
<td>100.0%</td>
<td>28.3%</td>
<td>71.7%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 8: Performance of Differently Sized EV Fleets in Base Case 1 under Type E EV Charging (Daily Perfect Tracking)

<table>
<thead>
<tr>
<th>Base Case 1 EV Charging Type E</th>
<th>Units</th>
<th>EV Charging From Renewable Energy</th>
<th>EV Charging From Thermal Energy</th>
<th>Total EV Charging Energy</th>
<th>Unused Curtained Energy</th>
<th>Used Curtained Energy</th>
<th>Total Curtained Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% EV Charging (GWh)</td>
<td>58</td>
<td>47</td>
<td>105</td>
<td></td>
<td>152</td>
<td>58</td>
<td>210</td>
</tr>
<tr>
<td>100% EV Charging (GWh)</td>
<td>98</td>
<td>112</td>
<td>210</td>
<td></td>
<td>112</td>
<td>98</td>
<td>210</td>
</tr>
<tr>
<td>200% EV Charging (GWh)</td>
<td>151</td>
<td>269</td>
<td>420</td>
<td></td>
<td>59</td>
<td>151</td>
<td>210</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Base Case 1 EV Charging Type E</th>
<th>% of Total</th>
<th>Energy Usage</th>
<th>Energy Usage</th>
<th>Total Energy Usage</th>
<th>Curtained Energy</th>
<th>Curtained Energy</th>
<th>Curtained Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% EV Charging</td>
<td>54.8%</td>
<td>54.8%</td>
<td>45.2%</td>
<td>100.0%</td>
<td>72.6%</td>
<td>27.4%</td>
<td>100.0%</td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>46.7%</td>
<td>46.7%</td>
<td>53.3%</td>
<td>100.0%</td>
<td>53.3%</td>
<td>46.7%</td>
<td>100.0%</td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>35.9%</td>
<td>35.9%</td>
<td>64.1%</td>
<td>100.0%</td>
<td>28.3%</td>
<td>71.7%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
### Table 9: Performance of Differently Sized EV Fleets in Base Case 2 under Type D EV Charging (Profile 2)

<table>
<thead>
<tr>
<th>Base Case 2 EV Charging Type D</th>
<th>Units</th>
<th>EV Charging From Renewable</th>
<th>EV Charging From Thermal</th>
<th>Total EV Charging</th>
<th>Unused Curtailed</th>
<th>Used Curtailed</th>
<th>Total Curtailed</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% EV Charging</td>
<td>(GWh)</td>
<td>188</td>
<td>180</td>
<td>368</td>
<td>548</td>
<td>188</td>
<td>736</td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>(GWh)</td>
<td>337</td>
<td>399</td>
<td>736</td>
<td>399</td>
<td>337</td>
<td>736</td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>(GWh)</td>
<td>532</td>
<td>940</td>
<td>1,471</td>
<td>204</td>
<td>532</td>
<td>736</td>
</tr>
<tr>
<td>50% EV Charging % of Total</td>
<td></td>
<td>51.0%</td>
<td>49.0%</td>
<td>100.0%</td>
<td>74.5%</td>
<td>25.5%</td>
<td>100.0%</td>
</tr>
<tr>
<td>100% EV Charging % of Total</td>
<td></td>
<td>45.8%</td>
<td>54.2%</td>
<td>100.0%</td>
<td>54.2%</td>
<td>45.8%</td>
<td>100.0%</td>
</tr>
<tr>
<td>200% EV Charging % of Total</td>
<td></td>
<td>36.1%</td>
<td>63.9%</td>
<td>100.0%</td>
<td>27.7%</td>
<td>72.3%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

### Table 10: Performance of Differently Sized EV Fleets in Base Case 2 under Type E EV Charging (Daily Perfect Tracking)

<table>
<thead>
<tr>
<th>Base Case 2 EV Charging Type F</th>
<th>Units</th>
<th>EV Charging From Renewable</th>
<th>EV Charging From Thermal</th>
<th>Total EV Charging</th>
<th>Unused Curtailed</th>
<th>Used Curtailed</th>
<th>Total Curtailed</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% EV Charging</td>
<td>(GWh)</td>
<td>232</td>
<td>135</td>
<td>368</td>
<td>503</td>
<td>232</td>
<td>736</td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>(GWh)</td>
<td>392</td>
<td>343</td>
<td>736</td>
<td>343</td>
<td>392</td>
<td>736</td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>(GWh)</td>
<td>597</td>
<td>875</td>
<td>1,471</td>
<td>139</td>
<td>597</td>
<td>736</td>
</tr>
<tr>
<td>50% EV Charging % of Total</td>
<td></td>
<td>63.2%</td>
<td>36.8%</td>
<td>100.0%</td>
<td>68.4%</td>
<td>31.6%</td>
<td>100.0%</td>
</tr>
<tr>
<td>100% EV Charging % of Total</td>
<td></td>
<td>53.3%</td>
<td>46.7%</td>
<td>100.0%</td>
<td>46.7%</td>
<td>53.3%</td>
<td>100.0%</td>
</tr>
<tr>
<td>200% EV Charging % of Total</td>
<td></td>
<td>40.6%</td>
<td>59.4%</td>
<td>100.0%</td>
<td>18.9%</td>
<td>81.1%</td>
<td>100.0%</td>
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</table>

### Table 11: Performance of Differently Sized EV Fleets in Base Case 3 under Type D EV Charging (Profile 2)

<table>
<thead>
<tr>
<th>Base Case 3 EV Charging Type D</th>
<th>Units</th>
<th>EV Charging From Renewable</th>
<th>EV Charging From Thermal</th>
<th>Total EV Charging</th>
<th>Unused Curtailed</th>
<th>Used Curtailed</th>
<th>Total Curtailed</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% EV Charging</td>
<td>(GWh)</td>
<td>79</td>
<td>121</td>
<td>200</td>
<td>322</td>
<td>79</td>
<td>401</td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>(GWh)</td>
<td>144</td>
<td>257</td>
<td>401</td>
<td>257</td>
<td>144</td>
<td>401</td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>(GWh)</td>
<td>238</td>
<td>563</td>
<td>801</td>
<td>163</td>
<td>238</td>
<td>401</td>
</tr>
<tr>
<td>50% EV Charging % of Total</td>
<td></td>
<td>39.4%</td>
<td>60.6%</td>
<td>100.0%</td>
<td>80.3%</td>
<td>19.7%</td>
<td>100.0%</td>
</tr>
<tr>
<td>100% EV Charging % of Total</td>
<td></td>
<td>36.0%</td>
<td>64.0%</td>
<td>100.0%</td>
<td>64.0%</td>
<td>36.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>200% EV Charging % of Total</td>
<td></td>
<td>29.7%</td>
<td>70.3%</td>
<td>100.0%</td>
<td>40.6%</td>
<td>59.4%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
### Table 12: Performance of Differently Sized EV Fleets in Base Case 3 under Type E EV Charging (Daily Perfect Tracking)

<table>
<thead>
<tr>
<th>Base Case 3</th>
<th>EV Charging Type F</th>
<th>Units</th>
<th>EV Charging From Renewable Energy</th>
<th>EV Charging From Thermal Energy</th>
<th>Total EV Charging Energy</th>
<th>Unused Curtailed Energy</th>
<th>Used Curtailed Energy</th>
<th>Total Curtailed Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daily Perfect Tracking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% EV Charging</td>
<td>(GWh)</td>
<td>116</td>
<td>84</td>
<td>200</td>
<td>285</td>
<td>116</td>
<td>401</td>
<td></td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>(GWh)</td>
<td>199</td>
<td>202</td>
<td>401</td>
<td>202</td>
<td>199</td>
<td>401</td>
<td></td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>(GWh)</td>
<td>306</td>
<td>495</td>
<td>801</td>
<td>94</td>
<td>306</td>
<td>401</td>
<td></td>
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<tr>
<td>50% EV Charging</td>
<td>% of Total</td>
<td>58.0%</td>
<td>42.0%</td>
<td>100.0%</td>
<td>71.0%</td>
<td>29.0%</td>
<td>100.0%</td>
<td></td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>% of Total</td>
<td>49.6%</td>
<td>50.4%</td>
<td>100.0%</td>
<td>50.4%</td>
<td>49.6%</td>
<td>100.0%</td>
<td></td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>% of Total</td>
<td>38.2%</td>
<td>61.8%</td>
<td>100.0%</td>
<td>23.6%</td>
<td>76.4%</td>
<td>100.0%</td>
<td></td>
</tr>
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### Table 13: Performance of Differently Sized EV Fleets in Base Case 4 Profile under Type D EV Charging (Profile 2)

<table>
<thead>
<tr>
<th>Base Case 4</th>
<th>EV Charging Type D</th>
<th>Units</th>
<th>EV Charging From Renewable Energy</th>
<th>EV Charging From Thermal Energy</th>
<th>Total EV Charging Energy</th>
<th>Unused Curtailed Energy</th>
<th>Used Curtailed Energy</th>
<th>Total Curtailed Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30% Day, 70% Night, 0% Peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% EV Charging</td>
<td>(GWh)</td>
<td>46</td>
<td>85</td>
<td>131</td>
<td>215</td>
<td>46</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>(GWh)</td>
<td>86</td>
<td>175</td>
<td>262</td>
<td>175</td>
<td>86</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>(GWh)</td>
<td>150</td>
<td>373</td>
<td>523</td>
<td>112</td>
<td>150</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>50% EV Charging</td>
<td>% of Total</td>
<td>35.2%</td>
<td>64.8%</td>
<td>100.0%</td>
<td>82.4%</td>
<td>17.6%</td>
<td>100.0%</td>
<td></td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>% of Total</td>
<td>33.0%</td>
<td>67.0%</td>
<td>100.0%</td>
<td>67.0%</td>
<td>33.0%</td>
<td>100.0%</td>
<td></td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>% of Total</td>
<td>28.6%</td>
<td>71.4%</td>
<td>100.0%</td>
<td>42.8%</td>
<td>57.2%</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>

### Table 14: Performance of Differently Sized EV Fleets in Base Case 4 under Type E EV Charging (Daily Perfect Tracking)

<table>
<thead>
<tr>
<th>Base Case 4</th>
<th>EV Charging Type F</th>
<th>Units</th>
<th>EV Charging From Renewable Energy</th>
<th>EV Charging From Thermal Energy</th>
<th>Total EV Charging Energy</th>
<th>Unused Curtailed Energy</th>
<th>Used Curtailed Energy</th>
<th>Total Curtailed Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daily Perfect Tracking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% EV Charging</td>
<td>(GWh)</td>
<td>72</td>
<td>59</td>
<td>131</td>
<td>189</td>
<td>72</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>(GWh)</td>
<td>121</td>
<td>141</td>
<td>262</td>
<td>141</td>
<td>121</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>(GWh)</td>
<td>185</td>
<td>338</td>
<td>523</td>
<td>77</td>
<td>185</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>50% EV Charging</td>
<td>% of Total</td>
<td>55.2%</td>
<td>44.8%</td>
<td>100.0%</td>
<td>72.4%</td>
<td>27.6%</td>
<td>100.0%</td>
<td></td>
</tr>
<tr>
<td>100% EV Charging</td>
<td>% of Total</td>
<td>46.3%</td>
<td>53.7%</td>
<td>100.0%</td>
<td>53.7%</td>
<td>46.3%</td>
<td>100.0%</td>
<td></td>
</tr>
<tr>
<td>200% EV Charging</td>
<td>% of Total</td>
<td>35.3%</td>
<td>64.7%</td>
<td>100.0%</td>
<td>29.3%</td>
<td>70.7%</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>
As shown in these tables, only a portion of the EV Charging is met by the Curtailed Energy (from Renewable Generation). Part of EV Charging has to be met by the Thermal Energy (areas under the red line and above the blue curve as show in the Duration Curve charts).

Although higher annual EV charging levels capture more of the potentially curtailed renewable energy, they also result in higher demand for Thermal Energy, which is mainly non-renewable (i.e., fossil-based) energy.

The main reason is that at higher levels of EV Charging, there will be many hours where the EV Charging will be greater than the available renewable energy, and hence, require more fossil-based generation.

3.6 Energy Storage and EV Charging

3.6.1 Role of Storage

Energy Storage (ES) Systems can help with reducing the curtailment of renewable energy. The amount of reduction in curtailment would depend on the technical characteristics of the ES system, which includes its energy rating (MWh), its charge and discharge capacity (MW), and its round-trip efficiency, representing the amount of energy lost in the complete storage cycle. To correctly size the ES system to reduce curtailment and assist with EV charging, one needs to examine the hourly profile and amount of the expected curtailed energy and the size of the EV fleet.

In this section we investigate the role of ES and the reduction in curtailed energy that can be achieved by storage of different sizes. It should be noted that our investigation is limited in scope and does not involve any comprehensive look into the role and impact of ES systems on the grid, but rather takes a narrow look at ES systems as complementary components elements to EV charging.

As such, ES systems can be used to store electric energy from any surplus renewable energy that is not already captured by EV charging, for later discharge and capture by EV charging during the low renewable supply periods. Hence, we are only considering a very limited role for ES systems in this study. The findings in this section should not be considered as making any conclusions on the overall cost-benefit of grid scale ES systems on a power grid.

3.6.2 Storage Assumptions

An ES system is characterized by four main attributes:

- Storage energy capacity (MWh): how much energy can be stored in the ES system
Storage charge rate (MW): how fast energy can be stored per unit of time

Storage discharge rate (MW): how fast energy can be discharged per unit of time

Round-trip efficiency (%): energy loss in a charge to discharge cycle

We start with a reference storage size, i.e., the Baseline Storage. In the context of supplementing EV charging, the following assumptions were made.

- Storage Charge: only occurs when there is surplus renewable energy on the grid (from the potential curtailed renewable energy – after EV charging has occurred).
- Storage Discharge: only occurs when the grid is able to absorb more renewable energy after all potentially curtailed energy has been exhausted by EV Charging.
- The Baseline Storage system is sized at 1000 MWh (1 GWh) of capacity, with a Charge and Discharge Rate of 250 MW. If empty, it can completely fill-in in 4 hours, and if full, it can completely empty-out in 4 hours (at the full charge-discharge rate).
- For this analysis, storage losses (round trip efficiency) are ignored, although if we assume linear losses, it can be easily estimated.
- For comparison, we also consider other storage sizes in addition to the 1000 MWh storage, but maintain the same capacity-to-rate ratio (i.e. storage capacity/charge-discharge rate = 4).
- The hour-to-hour storage operation is defined by the following formulation:
  \[ S[h] = S[h-1] + C[h] - D[h] \]
  Where:
  - \( S \): Stored Energy (kWh)
  - \( h \): Hour
  - \( C \): Charge = Surplus Curtailed Energy (kWh)
  - \( D \): Discharge = EV Charging needed over Curtailed Energy (kWh)
  Subject to following constraints:
  - \( 0 \leq S[h] \leq S_{max} \)
  - \( 0 \leq C[h] \leq C_{max} \)
  - \( 0 \leq D[h] \leq D_{max} \)
  Where
  - \( S_{max} \): Maximum Storage (stored energy) size
3.6.3 What is the impact of storage?

The Baseline storage operation was simulated using a spreadsheet-model, which charged and discharged the storage on an hour by hour basis for the whole year. The hourly charge amount was the maximum of Charge Rate and the surplus curtailed energy after EV charging. The hourly discharge amount was the maximum of Discharge Rate and the remaining EV charging needs after exhaustion of curtailed energy.

Figure 18 shows the storage behavior for the last week of June, i.e., hourly charge, discharge and storage levels, for the Baseline Storage assuming Base Case 2 under Type B Perfect Tracking Profile.
ES stored energy fluctuates between its maximum capacity (1000 MWh for Baseline Storage) and its minimum capacity (zero). The ES system stores energy when there is surplus curtailed energy, until it becomes full. The stored energy is drawn down when curtailed energy becomes insufficient to be used for EV charging.

In both weeks shown in the previous figures, the Baseline Storage stays full for prolonged periods. At such times, any additional surplus curtailed energy goes unused (gets spilled).

In the Appendix (Section 8), we provide additional charts that depict storage operations under different weekly curtailed energy load shapes.

### 3.6.4 What is a Good Size for the Storage Charging Rate?

As shown in Figure 19 (Hourly Curtained Energy Duration Curve), the 250 MW storage charging rate of the Baseline Storage should be able to capture most of the hourly curtailed energy. The highest level of hourly curtailed energy is about 500 MWh; therefore, ES systems with charging rates above 500 MWh/Hour would offer no additional value.

![Figure 19: Impact of Storage on Curtained Energy Capture](image-url)
3.6.5 Storage Size Impact

In addition to the Baseline Storage, we considered other storage sizes. To enable simple comparisons among the storage sizes, we maintained the same ratio of storage energy size to storage charge/discharge rate of 4. However, it should be noted that as shown in the earlier slide, charge rates of greater than about 500 MWh will not make much of a difference. In fact, the ES charging rate does not need to be greater than the Maximum of the Difference between Hourly Curtailed Energy and Hourly EV Charging Rate.

The following tables show the impact of Storage Sizes (from 0 to 10,000 MWh) under different levels of EV charging (100%, 50% and 200% of Base Case 2 using the Annual Perfect Tracking EV Charging Profile).

Table 15: Impact of Storage Size in Base Case 2 with Annual Perfect Tracking at 100% Annual Level

<table>
<thead>
<tr>
<th>Storage Size (MWh)</th>
<th>Max Charge/Discharge (MW)</th>
<th>Units</th>
<th>EV Charging from Renewable Energy (MWh)</th>
<th>EV Charging from Thermal Energy (MWh)</th>
<th>Total EV Charging Energy (MWh)</th>
<th>Used Curtailed Energy (MWh)</th>
<th>Unused Curtailed Energy (MWh)</th>
<th>Total Curtailed Energy (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>(MWh)</td>
<td>339,298</td>
<td>396,364</td>
<td>735,662</td>
<td>339,298</td>
<td>396,364</td>
<td>735,662</td>
</tr>
<tr>
<td>1,000</td>
<td>250</td>
<td>(MWh)</td>
<td>402,203</td>
<td>333,459</td>
<td>735,662</td>
<td>403,203</td>
<td>332,459</td>
<td>735,662</td>
</tr>
<tr>
<td>2,000</td>
<td>500</td>
<td>(MWh)</td>
<td>422,474</td>
<td>313,188</td>
<td>735,662</td>
<td>424,474</td>
<td>311,188</td>
<td>735,662</td>
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<tr>
<td>4,000</td>
<td>1,000</td>
<td>(MWh)</td>
<td>450,575</td>
<td>285,086</td>
<td>735,662</td>
<td>454,575</td>
<td>281,086</td>
<td>735,662</td>
</tr>
<tr>
<td>6,000</td>
<td>1,500</td>
<td>(MWh)</td>
<td>471,803</td>
<td>263,859</td>
<td>735,662</td>
<td>477,803</td>
<td>257,859</td>
<td>735,662</td>
</tr>
<tr>
<td>8,000</td>
<td>2,000</td>
<td>(MWh)</td>
<td>489,803</td>
<td>245,859</td>
<td>735,662</td>
<td>497,803</td>
<td>237,859</td>
<td>735,662</td>
</tr>
<tr>
<td>10,000</td>
<td>2,500</td>
<td>(MWh)</td>
<td>507,803</td>
<td>227,859</td>
<td>735,662</td>
<td>517,803</td>
<td>217,859</td>
<td>735,662</td>
</tr>
</tbody>
</table>

% of Total

<table>
<thead>
<tr>
<th>Storage Size (MWh)</th>
<th>Max Charge/Discharge (MW)</th>
<th>Units</th>
<th>EV Charging from Renewable Energy (MWh)</th>
<th>EV Charging from Thermal Energy (MWh)</th>
<th>Total EV Charging Energy (MWh)</th>
<th>Used Curtailed Energy (MWh)</th>
<th>Unused Curtailed Energy (MWh)</th>
<th>Total Curtailed Energy (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>(MWh)</td>
<td>46.1%</td>
<td>53.9%</td>
<td>100.0%</td>
<td>46.1%</td>
<td>53.9%</td>
<td>100.0%</td>
</tr>
<tr>
<td>1,000</td>
<td>250</td>
<td>(MWh)</td>
<td>54.7%</td>
<td>45.3%</td>
<td>100.0%</td>
<td>54.8%</td>
<td>45.2%</td>
<td>100.0%</td>
</tr>
<tr>
<td>2,000</td>
<td>500</td>
<td>(MWh)</td>
<td>57.4%</td>
<td>42.6%</td>
<td>100.0%</td>
<td>57.7%</td>
<td>42.3%</td>
<td>100.0%</td>
</tr>
<tr>
<td>4,000</td>
<td>1,000</td>
<td>(MWh)</td>
<td>57.4%</td>
<td>42.6%</td>
<td>100.0%</td>
<td>57.7%</td>
<td>42.3%</td>
<td>100.0%</td>
</tr>
<tr>
<td>6,000</td>
<td>1,500</td>
<td>(MWh)</td>
<td>64.1%</td>
<td>35.9%</td>
<td>100.0%</td>
<td>64.9%</td>
<td>35.1%</td>
<td>100.0%</td>
</tr>
<tr>
<td>8,000</td>
<td>2,000</td>
<td>(MWh)</td>
<td>66.6%</td>
<td>33.4%</td>
<td>100.0%</td>
<td>67.7%</td>
<td>32.3%</td>
<td>100.0%</td>
</tr>
<tr>
<td>10,000</td>
<td>2,500</td>
<td>(MWh)</td>
<td>69.0%</td>
<td>31.0%</td>
<td>100.0%</td>
<td>70.4%</td>
<td>29.6%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
### Table 16: Impact of Storage Size in Base Case 2 with Annual Perfect Tracking at 50% Annual Level

<table>
<thead>
<tr>
<th>Storage Size (MWh)</th>
<th>Max Charge/Discharge (MW)</th>
<th>EV Charging From Renewable Energy (MWh)</th>
<th>EV Charging From Thermal Energy (MWh)</th>
<th>Total Charging Energy (MWh)</th>
<th>Curtailed Energy Used (MWh)</th>
<th>Curtailed Energy Unused (MWh)</th>
<th>Total Energy (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>185,559</td>
<td>182,272</td>
<td>367,831</td>
<td>185,559</td>
<td>550,103</td>
<td>735,662</td>
</tr>
<tr>
<td>1,000</td>
<td>250</td>
<td>247,583</td>
<td>120,248</td>
<td>367,831</td>
<td>248,583</td>
<td>487,079</td>
<td>735,662</td>
</tr>
<tr>
<td>2,000</td>
<td>500</td>
<td>272,336</td>
<td>95,495</td>
<td>367,831</td>
<td>274,336</td>
<td>461,326</td>
<td>735,662</td>
</tr>
<tr>
<td>4,000</td>
<td>1,000</td>
<td>296,829</td>
<td>71,002</td>
<td>367,831</td>
<td>300,829</td>
<td>434,832</td>
<td>735,662</td>
</tr>
<tr>
<td>6,000</td>
<td>1,500</td>
<td>313,380</td>
<td>54,451</td>
<td>367,831</td>
<td>319,380</td>
<td>416,281</td>
<td>735,662</td>
</tr>
<tr>
<td>8,000</td>
<td>2,000</td>
<td>327,380</td>
<td>40,451</td>
<td>367,831</td>
<td>335,380</td>
<td>400,281</td>
<td>735,662</td>
</tr>
<tr>
<td>10,000</td>
<td>2,500</td>
<td>341,380</td>
<td>26,451</td>
<td>367,831</td>
<td>351,380</td>
<td>384,281</td>
<td>735,662</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage Size (MWh)</th>
<th>Max Charge/Discharge (MW)</th>
<th>% of Total</th>
<th>% of Total</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>50.4%</td>
<td>49.6%</td>
<td>100.0%</td>
</tr>
<tr>
<td>1,000</td>
<td>250</td>
<td>67.3%</td>
<td>32.7%</td>
<td>100.0%</td>
</tr>
<tr>
<td>2,000</td>
<td>500</td>
<td>74.0%</td>
<td>26.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>4,000</td>
<td>1,000</td>
<td>80.7%</td>
<td>19.3%</td>
<td>100.0%</td>
</tr>
<tr>
<td>6,000</td>
<td>1,500</td>
<td>85.2%</td>
<td>14.8%</td>
<td>100.0%</td>
</tr>
<tr>
<td>8,000</td>
<td>2,000</td>
<td>89.0%</td>
<td>11.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>10,000</td>
<td>2,500</td>
<td>92.8%</td>
<td>7.2%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
As can be seen, increasing the storage size helps reduce curtailed energy and thereby shifts generation from utilizing thermal resources to renewable resources. However, it appears that this favorable relationship is less than proportional and is subject to diminishing marginal returns as storage size increases. That is, doubling the energy storage size does not translate to doubling the reduction in curtailed energy and as the EVEV charging level increases, the impact of doubling the size of storage decreases. In fact, the greatest impact is the low 50% EV charging level.

The following figures may help provide an explanation for this phenomenon. As shown in the following figure, the main reason appears to be the fact that some days have clustering of many hours of high curtailed energy, resulting in filling up of storage to the limit; and there are also days with very little Curtailed Energy.
A 1000 MW ES system hits the limit during many hours of the year, as shown in Figure 21.
Even a much larger storage capacity (e.g., 10,000 MWh) hits full utilization, albeit in fewer hours during the year shown in Figure 22.

![Figure 22: Storage Size Can Be a Constraint Even for Very Large ES Systems](image)

Figure 23 and Figure 24 illustrate the storage behavior (storage charging and storage level) during the first seven days of the year for 1000 MWh and 10,000 MWh ES systems, respectively.
Figure 23: 1000-MWh Storage Behavior during the First 7 Days of the Year

Figure 24: 10,000-MWh Storage Behavior during the First 7 Days of the Year
3.6.6 Observations on Storage Impact

- Larger ES Sizes:
  - Enable higher utilization of potential Curtailed Energy, and
  - Reduce the amount of additional thermal energy needed for EV Charging.

- Storage Charge Rate (MW) can be kept as small as the maximum delta between hourly curtailed energy and EV charging without any impact.

Higher storage size (MWh) will capture more of the curtailed energy for EV Charging, but storage size needs to be many times the size of daily EV Charging to capture most of the curtailed energy. This is simply due to the fact that, at least in this study, the hours when renewable energy is curtailed, and the size of curtailment, in the corresponding base cases do not follow any particular pattern and appear to be intermittent, and as such, do not line up well with any daily pattern of EV charging. As noted before, the Best We Can Do is a Daily Perfect Tracking, which actually results in widely different charging patterns from day to day. As a result, for a fixed daily EV charging patterns, there may be many hours where level of curtailed energy is much higher than the EV charging levels at those hours. As the previous figures illustrate, even very large energy storage systems can fill up fast and remain full for prolonged periods, and a full storage cannot capture any unused curtailed energy.

3.7 Impact on Bulk Power System Performance

This section compares the impact of selected EV profiles on several aspects of bulk power system performance, including:

- Thermal Generation (GWh)
- Renewable Generation (GWh)
- Curtailed Energy (GWh)
- CO2 Emissions (1000 Tons)
- Annual Fuel Consumption (1000 MMBtu)
- Variable Cost of Operations ($M)

It should be noted that the annual level of EV Charging is set equal to the total curtailed energy in the corresponding Base Case. As a result, we are comparing the system attributes using different levels of EV Charging for each Base Case scenarios. Higher or lower EV fleet sizes will have a smaller or greater impact compared to these results.

The system-level impacts were only determined for four of the six EV charging profiles:
A: Annual Uniform Charging,  
B: Annual Perfect Tracking,  
C: Annual Profile 1, and  
D: Annual Profile 2.  

The main reason is that the GE MAPS production costing simulation was used for the analysis of these profiles only. The other two profiles (E: 85% Evening Profile and F: Daily Perfect Tracking), were evaluated using only a spreadsheet, which did not allow for determination of system-level performance impacts.

The following tables present the values of several system performance attributes for each Base Case under the selected profiles, both in absolute and relative terms.

### Table 18: System Level Performance Impacts of EV Charging Profiles (Absolute Values)

<table>
<thead>
<tr>
<th>Case</th>
<th>EV Profile</th>
<th>Thermal Generation (GWh)</th>
<th>Delivered Renewable Generation (GWh)</th>
<th>Curtailed Energy (GWh)</th>
<th>CO2 Emissions (1000 Tons)</th>
<th>Fuel Consumption (1000 MMBtu)</th>
<th>Variable Operating Costs ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1 No EV</td>
<td>No EV Charging</td>
<td>6,185</td>
<td>1,896</td>
<td>210</td>
<td>5,379</td>
<td>65,525</td>
<td>803</td>
</tr>
<tr>
<td>Base 1 EV A</td>
<td>Annual Uniform Charging</td>
<td>6,355</td>
<td>1,936</td>
<td>170</td>
<td>5,501</td>
<td>67,464</td>
<td>829</td>
</tr>
<tr>
<td>Base 1 EV B</td>
<td>Annual Perfect Tracking</td>
<td>6,314</td>
<td>1,977</td>
<td>129</td>
<td>5,488</td>
<td>67,031</td>
<td>817</td>
</tr>
<tr>
<td>Base 1 EV C</td>
<td>Annual Profile 1</td>
<td>6,349</td>
<td>1,941</td>
<td>165</td>
<td>5,498</td>
<td>67,404</td>
<td>828</td>
</tr>
<tr>
<td>Base 1 EV D</td>
<td>Annual Profile 2</td>
<td>6,332</td>
<td>1,959</td>
<td>147</td>
<td>5,496</td>
<td>67,237</td>
<td>823</td>
</tr>
<tr>
<td>Base 2 No EV</td>
<td>No EV Charging</td>
<td>5,641</td>
<td>2,443</td>
<td>736</td>
<td>4,961</td>
<td>59,295</td>
<td>750</td>
</tr>
<tr>
<td>Base 2 EV A</td>
<td>Annual Uniform Charging</td>
<td>6,079</td>
<td>2,738</td>
<td>440</td>
<td>5,294</td>
<td>64,412</td>
<td>824</td>
</tr>
<tr>
<td>Base 2 EV B</td>
<td>Annual Perfect Tracking</td>
<td>6,039</td>
<td>2,779</td>
<td>399</td>
<td>5,274</td>
<td>63,961</td>
<td>813</td>
</tr>
<tr>
<td>Base 2 EV C</td>
<td>Annual Profile 1</td>
<td>6,080</td>
<td>2,737</td>
<td>442</td>
<td>5,298</td>
<td>64,427</td>
<td>823</td>
</tr>
<tr>
<td>Base 2 EV D</td>
<td>Annual Profile 2</td>
<td>6,041</td>
<td>2,777</td>
<td>401</td>
<td>5,277</td>
<td>63,973</td>
<td>812</td>
</tr>
<tr>
<td>Base 3 No EV</td>
<td>No EV Charging</td>
<td>5,666</td>
<td>2,417</td>
<td>401</td>
<td>5,020</td>
<td>59,715</td>
<td>733</td>
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<tr>
<td>Base 3 EV A</td>
<td>Annual Uniform Charging</td>
<td>5,941</td>
<td>2,542</td>
<td>276</td>
<td>5,238</td>
<td>62,926</td>
<td>775</td>
</tr>
<tr>
<td>Base 3 EV B</td>
<td>Annual Perfect Tracking</td>
<td>5,906</td>
<td>2,578</td>
<td>240</td>
<td>5,226</td>
<td>62,550</td>
<td>766</td>
</tr>
<tr>
<td>Base 3 EV C</td>
<td>Annual Profile 1</td>
<td>5,946</td>
<td>2,537</td>
<td>281</td>
<td>5,237</td>
<td>62,969</td>
<td>775</td>
</tr>
<tr>
<td>Base 3 EV D</td>
<td>Annual Profile 2</td>
<td>5,923</td>
<td>2,561</td>
<td>257</td>
<td>5,230</td>
<td>62,719</td>
<td>767</td>
</tr>
<tr>
<td>Base 4 No EV</td>
<td>No EV Charging</td>
<td>5,883</td>
<td>2,200</td>
<td>262</td>
<td>5,181</td>
<td>62,143</td>
<td>757</td>
</tr>
<tr>
<td>Base 4 EV A</td>
<td>Annual Uniform Charging</td>
<td>6,081</td>
<td>2,264</td>
<td>198</td>
<td>5,332</td>
<td>64,432</td>
<td>788</td>
</tr>
<tr>
<td>Base 4 EV B</td>
<td>Annual Perfect Tracking</td>
<td>6,050</td>
<td>2,295</td>
<td>167</td>
<td>5,321</td>
<td>64,096</td>
<td>778</td>
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<tr>
<td>Base 4 EV C</td>
<td>Annual Profile 1</td>
<td>6,079</td>
<td>2,266</td>
<td>196</td>
<td>5,330</td>
<td>64,401</td>
<td>787</td>
</tr>
<tr>
<td>Base 4 EV D</td>
<td>Annual Profile 2</td>
<td>6,058</td>
<td>2,286</td>
<td>176</td>
<td>5,324</td>
<td>64,191</td>
<td>781</td>
</tr>
</tbody>
</table>
Significant observations about the effect of EV Charging Profiles on system-level attributes are:

- Type B EV charging profile (Annual Perfect Tracking) has the most positive impact on system performance. It has the most delivered renewable energy, the least curtailment, least emissions, least fuel consumption for thermal plants, and lowest variable operating costs (excluding the PPA cost of the renewable energy).

- The Type A profile (Annual Uniform Charging) and type C profile (30% Day; 70% Night) have worst has the least attractive impact on system performance. It has the least delivered renewable energy, the most curtailment, most emissions, most fuel consumption for all thermal plants, and highest variable operating costs.

- The more realistic Annual Profile 2 (70% day time charging, 0% critical peak time charging, and 30% night time charging) comes very close to the Annual Perfect Tracking in terms of system-level performance impacts for all Base Cases.
EV charging increases both thermal generation and renewable utilization (i.e., less curtailment) for all Base Cases.

EV charging also increases CO2 emissions, fossil fuel consumption, and variable operating costs in all Base Cases. However, for a societal cost-benefit analysis, these impacts should be compared to the underlying costs and greenhouse gas emissions of equivalent fleet of conventional gasoline powered vehicles – an exercise that is beyond the scope of this project, and which also should include the associated costs and the environmental impact of gasoline refining.

The greatest changes in system-level performance due to EV charging occur in Base Case 2), relative to the other scenarios. This is because Base Case 2 has the highest level of total wind and solar energy, highest level of wind energy alone, and the most curtailed energy among all the cases. Based on the main assumption of this study, the size of the annual EV charging is set to the size of the total annual curtailed energy, and hence, the scenarios corresponding to the Base Case 2 also have the largest EV charging load added to the system, and thus making the greatest impact on the system.

The following figures provide a graphical presentation of system-wide performance impacts for these four EV charging profiled.
Figure 25: Impact of EV Charging Profiles on Thermal Generation

Figure 26: Impact of EV Charging Profiles on Thermal Generation Relative to the No EV Cases
Figure 27: Impact of EV Charging Profiles on Delivered Renewable Generation

Figure 28: Impact of EV Charging Profiles on Delivered Renewable Generation Relative to the No EV Cases
Figure 29: Impact of EV Charging Profiles on Curtailed Energy

Figure 30: Impact of EV Charging Profiles on Curtailed Energy Relative to the No EV Cases
Figure 31: Impact of EV Charging Profiles on CO2 Emissions

Figure 32: Impact of EV Charging Profiles on CO2 Emissions Relative to the No EV Cases
Figure 33: Impact of EV Charging Profiles on Fuel Consumption

Figure 34: Impact of EV Charging Profiles on Fuel Consumption Relative to the No EV Cases
It should be noted that in the last two preceding figures, the power purchase agreement (PPA) costs for wind and solar energy are not included in the variable operating cost calculations.
3.8 Implications of Lack of Seasonality of Load and Curtained Energy

One issue that merits discussion is whether adjusting EV charging profiles from month to month, instead of maintaining the same profile all year, will have a greater impact in terms of capturing potentially curtained renewable energy.

To address that question, the seasonality of load and curtained renewable energy in each No EV Base Case was investigated by comparing the monthly diurnal average of load and curtained energy across the month.

Figure 37 depicts the average diurnal (24-hour) load pattern for each month. Same load assumptions apply to all four No EV Base Cases and EV Charging Scenarios. It can readily be observed that except for the absolute values, the monthly diurnal load shapes are very similar, with relatively little seasonality, from month to month. In the diurnal shapes, each hour’s average load in each month is calculated by summing the loads for all such hours in the month and dividing by the number of days in the month.

![Figure 37: Monthly Average Hourly Load](image)

We next considered the daily patterns of curtained renewable energy across the months of the year for each of the Base Cases.
Graphical representations of simple average hourly curtailed renewable energy in each month for each No EV Base Case are shown in Figure 38, Figure 40, Figure 42, and Figure 44. In these monthly traces, there appears to be wide variation in absolute hourly averages from month to month, although the overall shapes are similar. When comparing to the average hourly load shapes, one can observe that most curtailment occurs during hours of low load. The following figures also show that with higher penetrations of renewable energy (Base Cases 2, and 3), more and more curtailment occurs even in high load periods.

The main conclusion is that the diurnal pattern of load and curtailed energy, although different in absolute terms, have similar shapes across the months. In other words, the diurnal load and curtailed energy patterns lack seasonality. Hence, under the assumptions that the daily EV charging patterns will not change from day to day, then an EV charging program developed by policy makers (based on incentives or time or use pricing) meant to capture the curtailed renewable energy, would not need to take into account seasonality.

Also included are Figure 39, Figure 41, Figure 43, and Figure 45, which for each Base Case show the daily EV charging patterns under different EV charging profiles compared to the annual average hourly curtailed energy. As can be observed, the Annual Perfect Tracking Profile, by definition, perfectly matches the annual average hourly curtailed energy in each scenario. These findings indicate that the average monthly diurnal (24-hour) patterns of curtailed energy do not change from month to month and are very close to the average annual diurnal patterns of curtailed energy. The implication is that an EV charging schedule designed based on the annual diurnal pattern of curtailed energy will not need to be adjusted on a month to month basis. Absence of seasonality (changes in diurnal patterns from month to month) would complicate design of EV charging schedules.

Among more “realistic” EV profiles, the Type D – Profile 2 (30% Day, 0% Peak, and 70% Night profile) is closest to mimicking the results of the Annual Perfect Tracking Profile.
**Figure 38: Base 1 Average Hourly Curtained Energy in each Month**

**Figure 39: Base 1 Average Hourly EV Charging**
Figure 40: Base 2 Average Hourly Curtailed Energy in each Month

Figure 41: Base 2 Average Hourly EV Charging
Figure 42: Base 3 Average Hourly Curtailed Energy in each Month

Figure 43: Base 3 Average Hourly EV Charging
Figure 44: Base 4 Average Hourly Curtailed Energy in each Month

Figure 45: Base 4 Average EV Charging
Key findings are:

Although they are different in absolute values, there are minimal seasonal/monthly variations in both hourly load patterns and in the diurnal curtailed energy patterns.

The implication is that daily patterns of load and curtailed energy in Oahu under different wind and solar integration scenarios do not change much from month to month. This result could be unique to Hawaii and other regions which lack seasonal extremes in their daily weather patterns.

The lack of seasonality in Oahu load shape and curtailed renewable energy patterns implies that:

- An Annual Perfect Tracking EV charging profile would come very close to the Best We Can Do, or the Daily Perfect Tracking.
- There is no significant benefit to be gained from adjusting EV charging profiles on a seasonal basis. The same EV charging profile could be used in each month of the year.

3.9 Impact of Lower Spinning Reserve Requirements from Thermal Generation on Curtailment of Renewable Energy

This section presents the results of investigation into shifting a portion of the system spinning reserves from baseload thermal generation to other resources. Spinning reserves are the portion of thermal generation that are online, but not loaded onto the grid, that can be rapidly brought online in response to other generation resource outages. It was anticipated that doing so would allow some thermal generators to be de-committed during some hours, and thereby reduce the curtailment of wind and solar energy.

The hourly spinning reserve requirements are set through a complex process to ensure the reliability of the system and availability of resources to mitigate sudden demand for power in the event of a generating unit trip loss or volatility of wind and solar resources. Consequently, different MW combinations of wind and solar energy in Oahu result in different hourly spinning reserve requirements.

Reducing spinning reserve requirements on thermal baseload units can be achieved by alternative operating reserve resources of various kinds, including supply-side resources, demand-side resources, and energy storage systems.

The idea investigated in this section is that reducing the spinning reserve requirements on thermal units ()by any means - such as demand response or energy storage – would reduce thermal units to be committed to meet those system spinning reserve requirements, and
thus result in lower curtailed renewable energy. In this investigation we are not concerned with how this shift in spinning reserve requirements is achieved, but rather, if such a reduction in thermal unit spinning reserve requirement were possible by any means, how much would it reduce renewable energy curtailment.

To test the hypothesis we made a number of GE MAPS runs where we reduced the thermal generation spinning reserve requirements by half. Table 20 and Table 21 present GE-MAPS run results where the original hourly spin requirements of Base Case 2 and Base Case 3 scenarios have been cut in half. Results are shown for the Type B EV Charging Profile (Perfect Annual Tracking) and the Type D EV Charging Profile 2 (70% Day, 0% Peak, and 30% Night). As shown in the following table, for the two Base Case 2 scenarios, we observe only a slight reduction in curtailed energy.

Key findings are:

- A reduction in spinning reserves from thermal generation results in reduction of curtailed energy both in the No EV Base Case scenarios and also in the examined EV Charging Profile scenarios.

- In Base Case 2 which has the highest level of wind and solar energy, cutting thermal generation spinning reserve requirement in half results in a 13% to 20% reduction in curtailed renewable energy.

- In Base Case 3, which has a lower level of wind and solar energy, cutting the thermal generation spinning reserve requirement in half reduces wind and solar curtailment by 7% to 9%.

### Table 20: Impact of Reduction of Spin Requirement on Base 2 Curtailment of Renewable Energy

<table>
<thead>
<tr>
<th>EV Charging Scenarios</th>
<th>Total Available Renewable Energy (MWh)</th>
<th>Total Renewable Generation (MWh)</th>
<th>Total Curtailed Renewable Energy (MWh)</th>
<th>Curtailed Energy as Percent of Available Energy</th>
<th>Curtailed Energy as Percent of Base with Half Spin</th>
<th>Curtailed Energy as Percent of Base with Full Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>No EV Charging</td>
<td>3,178,114</td>
<td>2,442,510</td>
<td>735,662</td>
<td>23.1%</td>
<td>100.0%</td>
<td>87.2%</td>
</tr>
<tr>
<td>Annual Perfect Tracking</td>
<td>3,178,114</td>
<td>2,778,802</td>
<td>399,364</td>
<td>12.6%</td>
<td>54.3%</td>
<td>44.6%</td>
</tr>
<tr>
<td>Profile 2 (30% Day, 0% Peak, 70% Night)</td>
<td>3,178,114</td>
<td>2,776,758</td>
<td>401,409</td>
<td>12.6%</td>
<td>54.6%</td>
<td>43.9%</td>
</tr>
<tr>
<td>(Half Spin) with No EV Charging</td>
<td>3,178,114</td>
<td>2,536,448</td>
<td>641,724</td>
<td>20.2%</td>
<td>100.0%</td>
<td>87.2%</td>
</tr>
<tr>
<td>(Half Spin) with Annual Perfect Tracking</td>
<td>3,178,114</td>
<td>2,850,290</td>
<td>327,890</td>
<td>10.3%</td>
<td>51.1%</td>
<td>44.6%</td>
</tr>
<tr>
<td>(Half Spin) with Profile 2</td>
<td>3,178,114</td>
<td>2,855,426</td>
<td>322,753</td>
<td>10.2%</td>
<td>50.3%</td>
<td>43.9%</td>
</tr>
</tbody>
</table>
**Table 21: Impact of Reduction of Spin Requirement on Base 3 Curtailment of Renewable Energy**

<table>
<thead>
<tr>
<th>EV Charging Scenarios</th>
<th>Total Available Renewable Energy (MWh)</th>
<th>Total Renewable Generation (MWh)</th>
<th>Total Curtained Renewable Energy (MWh)</th>
<th>Curtained Energy as Percent of Available Energy</th>
<th>Curtained Energy as Percent of Base with Half Spin</th>
<th>Curtained Energy as Percent of Base with Full Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>No EV Charging</td>
<td>2,817,927</td>
<td>2,417,354</td>
<td>400,629</td>
<td>14.2%</td>
<td>100.0%</td>
<td>93.4%</td>
</tr>
<tr>
<td>Annual Perfect Tracking</td>
<td>2,817,927</td>
<td>2,578,150</td>
<td>239,839</td>
<td>8.5%</td>
<td>59.9%</td>
<td>54.8%</td>
</tr>
<tr>
<td>Profile 2 (30% Day, 0% Peak, 70% Night)</td>
<td>2,817,927</td>
<td>2,560,817</td>
<td>257,170</td>
<td>9.1%</td>
<td>64.2%</td>
<td>58.4%</td>
</tr>
<tr>
<td>(Half Spin) with No EV Charging</td>
<td>2,817,927</td>
<td>2,443,833</td>
<td>374,175</td>
<td>13.3%</td>
<td>100.0%</td>
<td>93.4%</td>
</tr>
<tr>
<td>(Half Spin) with Annual Perfect Tracking</td>
<td>2,817,927</td>
<td>2,598,625</td>
<td>219,388</td>
<td>7.8%</td>
<td>58.6%</td>
<td>54.8%</td>
</tr>
<tr>
<td>(Half Spin) with Profile 2</td>
<td>2,817,927</td>
<td>2,583,866</td>
<td>234,146</td>
<td>8.3%</td>
<td>62.6%</td>
<td>58.4%</td>
</tr>
</tbody>
</table>
4 Conclusions and Key Findings

This section provides a summary of the conclusions and key findings of the study.

Key findings of this study include the following:

- 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; only a fraction of the daily curtailed renewable energy of the corresponding No EV Base Case can be captured by EV charging. The fraction depends on the daily shape of the curtailed energy and the daily EV charging profile.

- The reason for partial capture of curtailed energy is due to the intermittent nature of the hourly patterns of wind and solar energy, which most of the times are either greater or less than the energy needed for EV charging. Therefore, wind and solar energy make only a partial contribution to the annual EV charging demand.

- Hence, EV charging that is required when renewable energy is not available must be provided by thermal generation.

- Annual EV Charging at higher levels (compared to the Annual Curtailed Energy) will capture more of the curtailed energy, but at the same time will result in demand for more Thermal Energy.

- The Type A and Type C EV charging profiles (Annual Uniform Charging and Profile 1) results in the smallest reduction in curtailed energy. Type C profile, which is relatively more realistic than Type A profile, can be considered a worst case bookend to the analysis.

- In contrast, the Type F EV charging profile (Daily Perfect Tracking/"Best That Can Be Done") 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 (30% day charging, 0% critical peak time charging, and 70% night charging) comes very close to the Annual Perfect Tracking in terms of system-level impacts.

- For all charging profiles, EV charging increases both thermal generation and also delivery of renewable generation (i.e., less curtailment) compared to the corresponding Base Cases.

- Addition of EV charging load to the system compared to the no EV charging in the corresponding base cases would appear to increase CO2 emissions, fossil fuel consumptions, and variable operating costs. However, such impacts would be expected from any load additions to the system. The proper comparison should be
based on wider societal cost-benefit analysis, where these impacts would be compared to the underlying costs and greenhouse gas emissions of equivalent fleet of conventional gasoline powered vehicles – an exercise that is beyond the scope of this project, and which also should include the associated costs and environmental impact of gasoline refining. Similarly, the costs and benefits of renewable energy additions should be compared to the costs and benefits of equivalent thermal generation that will be needed in the absence of any renewable energy additions to the system.

- Integrating EV charging into the grid will reduce the amount of curtailed renewable energy. However, because of the thermal generation required when renewable energy is not available; emissions, fuel at the power plant, and variable plant operating costs increase on an annual basis. This is partially offset by the gasoline and tailpipe emissions reduced, as well as the fossil fuel, refinery and distribution costs, and tailpipe emissions that are eliminated by using an electric vehicle. HNEI will reference life cycle analysis of conventional versus alternate fuel vehicles later in a separate report which will include the findings of this report.

- The greatest change in system-level attributes (emissions, fossil fuel reduction at the power plant, and variable plant operating costs) occurs in Base Case 2 related scenarios (300 MW Solar + 700 MW Wind). This case has the highest annual wind and solar energy available of all the scenarios studied.

Investigation of the seasonality of load and curtailed renewable energy indicates the following:

- Seasonal/monthly variations in hourly load patterns and diurnal curtailed energy patterns are very small, due to the fact that weather patterns in Oahu are nearly the same all year.

- The lack of seasonality in Oahu load shape and curtailed renewable energy patterns implies that:
  - An Annual Perfect Tracking (Type B) EV charging profile would come close to the Best We Can Do, i.e., the Daily Perfect Tracking profile (Type F), in terms of reducing curtailed renewable energy.
  - There is no apparent reason to adjust EV charging schedules on a monthly or seasonal basis, since the average daily system load and renewable energy curtailment patterns are nearly the same for all months of the year.

The key findings of the storage analysis are listed below:
 Assumes larger energy storage sizes:

- Enable higher utilization of potential curtailed energy, and
- Reduce the amount of additional thermal energy needed for EV charging

Storage Charge Rate (MW) can be kept as small as the maximum delta between hourly curtailed energy and hourly EV charging.

Higher storage size (MWh) will capture more of the curtailed energy for EV Charging, but storage sizes need to be many times the size of daily EV Charging to capture most of the curtailed energy.

Normally all required spinning reserves are provided by baseload thermal generators. The study examined the possibility of providing a portion of the spinning reserves from alternate resources – such as demand response (DR) or battery energy storage systems (BESS) - thereby reducing the spinning reserves allocated to thermal generators. The results show that:

- A reduction in spinning reserves from thermal generation results in reduction of curtailed energy both in the No EV Base Case scenarios and also in the examined EV Charging Profile scenarios.

- In Base Case 2 which has the highest level of wind and solar energy, cutting thermal generation spinning reserve requirement in half results in a 13% to 20% reduction in curtailed renewable energy.

- In Base Case 3, which has a lower level of wind and solar energy, cutting the thermal generation spinning reserve requirement in half reduces wind and solar curtailment by 7% to 9%.
5 Appendix A: GE MAPS Description

5.1 Application of GE MAPS to the Oahu EV Charging Study

Production cost modeling of the Oahu system was performed with the GE’s Multi Area Production Simulation (GE MAPS) software program. This commercially available modeling tool has a long history of governmental, regulatory, independent system operator and investor-owned electric utility applications. The production cost model provides the unit-by-unit production output (MW) on an hourly basis for an entire year of production (GWh of electricity production by each generation unit). The results also provide information about the variable cost of electricity production, emissions, fuel consumption, etc.

The overall simulation algorithm is based on standard least marginal cost operating practices. That is, generating units that can supply power at lower marginal cost of production are committed and dispatched before units with higher marginal cost of generation. Commitment and dispatch are constrained by physical limitations of the system, such as transmission thermal limits and minimum spinning reserves, as well as the physical limitations and characteristics of the power plants.

There are two primary sources of model uncertainty and error for production cost simulations:

- Marginal production-cost models consider heat rate and a variable O&M cost. However, the models do not include an explicit heat-rate penalty or an O&M penalty for increased maneuvering that may be a result of incremental system variability due to as-available renewable resources (in future scenarios).

- The production cost model requires input assumptions like forecasted fuel prices, forecasted system loads, estimated unit heat rates, maintenance and forced outage rates, etc. Variations from these assumptions could significantly alter the results of the study.

The simulation results provide insight into hour-to-hour operations, and how the commitment and dispatch may change subject to various changes, including equipment or operating practices. Since the production cost model depends on fuel price as an input, relative costs and changes in costs between alternative scenarios tend to produce better and more useful information than absolute costs. The results from the model approximate system dispatch and production, but do not necessarily identically match system behavior. The results do not necessarily reproduce accurate production costs on a unit-by-unit basis and do not accurately reproduce every aspect of system operation. However, the model reasonably quantifies the incremental changes in marginal cost, emissions, fossil fuel
consumption, and other operations metrics due to changes, such as higher levels of wind power.

# 5.2 Unique Features of GE MAPS

GE MAPS is a highly detailed model that calculates hour-by-hour production costs while recognizing the constraints on the dispatch of generation imposed by the transmission system. When the program was initially developed over thirty years ago, its primary use was as a generation and transmission planning tool to evaluate the impacts of transmission system constraints on the system production cost. In the current deregulated utility environment, the acronym GE MAPS may more appropriately stand for Market Assessment & Portfolio Strategies because of the model’s usefulness in studying issues such as market power, i.e., relative market share of competing generation entities, and the valuation of generating assets operating in a competitive environment.

The unique modeling capabilities of GE MAPS consist of a detailed electrical model of the entire transmission network, along with generation shift factors determined from a solved ac load flow, to calculate the real power flows for each generation dispatch. This enables the user to capture the economic penalties of re-dispatching the generation to satisfy transmission line flow limits and security constraints.

Separate dispatches of the interconnected system and the individual companies’ own load and generation are performed to determine the economic interchange of energy between companies. Several methods of cost reconstruction are available to compute the individual company costs in the total system environment. The chronological nature of the hourly loads is modeled for all hours in the year. In the electrical representation, the loads are modeled by individual nodes (or buses). An electrical bus represents points of common electrical connection between multiple electrical devices. In the context of GE MAPS, a node or bus is the points of interconnection between all elements on the power grid including transmission lines, typically represented by substations on the grid.

In addition to the traditional production costing results, MAPS can provide information on the hourly spot prices at individual buses and on the flows on selected transmission lines for all hours in the year, as well as identifying the companies responsible for the flows on a given line.

Because of its detailed representation of the transmission system, GE MAPS can be used to study issues that often cannot be adequately modeled with conventional production costing software. These issues include:

Market Structures – GE MAPS is being used extensively to model electricity market structures in different regions of the United States. It has been used to model the electricity

**Transmission Access** – GE MAPS calculates the hourly spot price ($/MWh) at each bus modeled, thereby defining a key component of the total avoided cost that is used in formulating contracts for transmission access by non-utility generators and independent power producers.

**Loop Flow or Uncompensated Wheeling** – The detailed transmission modeling and cost reconstruction algorithms in MAPS combine to identify the companies contributing to the flow on a given transmission line and to define the production cost impact of that loading.

**Transmission Bottlenecks** – GE MAPS can determine which transmission lines and interfaces in the system are bottlenecks and how many hours during the year these lines are limiting. Next, the program can be used to assess, from an economic point of view, the feasibility of various methods, such as transmission line upgrades or the installation of phase-angle regulators for alleviating bottlenecks.

**Evaluation of New Generation, Transmission, or Demand-Side Facilities** – GE MAPS can evaluate which of the available alternatives under consideration has the most favorable impact on system operation in terms of production costs and transmission system loading.

**Power Pooling** – The cost reconstruction algorithms in GE MAPS allow individual company performance to be evaluated with and without pooling arrangements, so that the benefits associated with pool operations can be defined.

### 5.3 Modeling Capabilities of GE MAPS

GE MAPS has evolved to study the management of a power system’s generation and transmission resources to minimize generation production costs while considering transmission security. The modeling capabilities of MAPS are summarized below.

**Time Frame** – One year to several years with ability to skip years.

**Company Models** – Up to 175 companies.

**Load Models** – Up to 175 load forecasts. The load shapes can include all 365 days or automatically compress to a typical week (seven different day shapes) per month. The day shapes can be further compressed from 24 to 12 hours, with bi-hourly loads.
**Generation** – Up to 7,500 thermal units, 500 pondage plants, 300 run-of-river plants, 50 energy-storage plants, 15 external contracts, 300 units jointly owned, and 2,000 fuel types. Thermal units have full and partial outages, daily planned maintenance, fixed and variable operating and maintenance costs, minimum down-time, must-run capability, and up to four fuels at a unit.

**Network Model** – Includes 50,000 buses, 100,000 lines, 145 phase-angle regulators, and 100 multi-terminal High-Voltage Direct Current lines. Line or interface transmission limits may be set using operating nomograms as well as thermal, voltage and stability limits. Line or interface limits may be varied by generation availability.

**Losses** - Transmission losses may vary as generation and loads vary, approximating the ac power flow behavior, or held constant, which is the usual production simulation assumption. The incremental loss factors are recalculated each hour to reflect their dependence on the generation dispatch.

**Marginal Costs** – Marginal costs for an increment such as 100 MW can be identified by running two cases, one 100 MW higher, with or without the same commitment and pumped-storage hydro schedule. A separate routine prepares the cost difference summaries. Hourly bus spot prices are also computed.

**Operating Reserves** – Modeled on an area, company, pool and system basis.

**Secure Dispatch** – Up to 5,000 lines and interfaces and nomograms may be monitored. Each study hour considers the effect of hundreds of different network outages.

Report Analyzer – MAPS allows the simulation results to be analyzed through a powerful report analyzer program, which incorporates full screen displays, customizable output reports, graphical displays and databases. The built-in programming language allows the user to rapidly create custom reports.

**Accounting** – Separate commitment and dispatches are done for the system and for the company own-load assumptions, allowing cost reconstruction and cost splitting on a licensee-agreed basis. External economy contracts are studied separately after the base dispatch each hour.

**Bottom Line** – Annual fuel plus O&M costs for each company, fuel consumption, and generator capacity factors.
6 Appendix B: Typical Weekly Dispatch

We have selected a few interesting weeks of Base Case 2 EV Profile graphically to demonstrate the Typical Weekly Dispatches. The Base Case 2 with type A EV Charging Profile (Annual Uniform Charging) was selected for simplicity of the presentation. The selected interesting weeks include the following:

- Week with the hour of most load energy
- Week with the hour of least load energy
- Week with the hour of most wind energy
- Week with the hour of most solar energy
- Week with the hour of most curtailed wind energy
- Week with the hour of most curtailed solar energy
- Week with most demand response
Figure 46: Week with Hour of Most Load Energy

Figure 47: Week with the Hour of Least Load Energy
Figure 48: Week with the Hour of Most Wind Energy

Figure 49: Week with the Hour of Most Solar Energy
Figure 50: Week with the Hour of Most Curtailed Wind Energy

Figure 51: Week with the Hour of Most Curtailed Solar Energy
**Figure 52: Week with the Hour of Most Demand Response**
7 Appendix C: Comparison of GE MAPS Results for the First Four Profiles

The following charts provide a comparison of available and delivered solar and wind energy across all the Base Cases and the first four EV charging profiles.
Figure 53: Annual Wind and Solar Utilization for Base Case 1 (Side by Side)

Figure 54: Annual Wind and Solar Utilization for Base Case 1 (Stacked)
Figure 55: Annual Wind and Solar Utilization for Base Case 2 (Side by Side)

Figure 56: Annual Wind and Solar Utilization for Base Case 2 (Stacked)
Figure 57: Annual Wind and Solar Utilization for Base Case 3 (Side by Side)

Figure 58: Annual Wind and Solar Utilization for Base Case 3 (Stacked)
Figure 59: Annual Wind and Solar Utilization for Base Case 4 (Side by Side)

Figure 60: Annual Wind and Solar Utilization for Base Case 4 (Stacked)
8 Appendix E: More Weekly Storage Charts

The storage charge and discharge behavior is very much dependent on the daily curtailed energy pattern, the EV charging pattern, and also the storage size and charge/discharge rates. Following figures illustrate the storage operations during selected weeks in Base Case 2 under 100% EV Charging Profile Type B (Annual Perfect Tracking). Charts are provided for weekly operation of a 1000 MWh-250 MW Storage.

As a result, as shown in the following charts, each weekly pattern appears to be different.

Figure 61: Storage Chart for Week # 19 of the Year 2015
Figure 62: Storage Chart for Week # 20 of the Year 2015
Figure 63: Storage Chart for Week # 30 of the Year 2015
Figure 64: Storage Chart for Week # 40 of the Year 2015
Figure 65: Storage Chart for Week # 50 of the Year 2015