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Executive Summary

Ascend Analytics (“Ascend”) of Boulder, Colorado, was selected by Hawaiian Electric Companies (“the Companies”) to perform modeling analysis on the Post-April PSIP Plans developed in the Companies’ December 2016 PSIP filing. Ascend performed modeling analysis using its PowerSimm software.

Ascend performed validation of resource plans developed by the Companies and the Companies’ consultant Energy and Environmental Economics (E3). The following plans were validated by Ascend’s PowerSimm software:

<table>
<thead>
<tr>
<th></th>
<th>Oahu (OAHU)</th>
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<tbody>
<tr>
<td></td>
<td>Post-April PSIP Plan</td>
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<tr>
<td></td>
<td>E3 Plan – Least cost resource plan without LNG</td>
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<tr>
<td></td>
<td>E3 Plan with LNG – least cost resource plan with LNG</td>
</tr>
<tr>
<td></td>
<td>Hawaii (HELCO)</td>
</tr>
<tr>
<td></td>
<td>Post-April PSIP Plan developed by the Companies</td>
</tr>
<tr>
<td></td>
<td>E3 Plan – least cost resource plan without LNG</td>
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<tr>
<td></td>
<td>Maui (MECO)</td>
</tr>
<tr>
<td></td>
<td>Post-April PSIP Plan developed by the Companies</td>
</tr>
<tr>
<td></td>
<td>E3 Plan – least cost resource plan without LNG</td>
</tr>
</tbody>
</table>

Table 1: Summary of the plans developed by the Companies and E3, which Ascend evaluated through Powersimm.

PowerSimm’s evaluation of the Post-April PSIP Plans and E3 Plans align with the general trends found in Companies’ evaluation of these plans through their Plexos model. As in the Plexos evaluations, PowerSimm found there to be only a marginal difference between the Oahu E3 Plan and the Oahu Post-April PSIP Plan, while calculating a significant reduction in costs for the Oahu E3 Plan with LNG relative to the Post-April PSIP Plan. For the Maui E3 Plan, PowerSimm calculated an 8% reduction in costs when compared with the Maui Post-April PSIP Plan, while Plexos results show an 7% reduction. For Hawaii, PowerSimm calculated a 2% reduction in total costs, and Plexos calculated a 9% reduction in total costs.

Ascend also utilized PowerSimm to evaluate the merits of adding flexible thermal units to Oahu’s thermal fleet. With Oahu’s high renewable penetration rates, thermal generation’s role shifts from meeting base load to complementing the increasing levels of intermittent renewable generation. Since wind and solar generation cannot be regulated to meet changes in load, thermal generation becomes a key asset in addressing the imbalances that arise between supply and load in a system with such variable outputs. To respond to these imbalances, thermal units have to be flexible, ramping up, ramping down, starting up and shutting off much more frequently than in the past. PowerSimm determined the optimal introduction of flexible thermal unit additions to Oahu’s preexisting thermal fleet. Ascend then compared Oahu’s forecasted costs with (1) its existing fleet, (2) the Post-April PSIP Plan’s updated fleet, and (3) the updated fleet developed by Ascend. The results show that the addition of flexible thermal units to the preexisting fleet can provide significant savings.

In addition to validating the Post-April PSIP Plans and E3 Plans, Ascend has further optimized the Post-April PSIP Plans by utilizing PowerSimm software to systematically incorporate uncertainty into the
planning process. By rigorously simulating the impact of weather on renewables and load, PowerSimm determined the need for substantial additions of batteries that can respond to the natural variability of high renewable penetration rates. Ascend has determined the economic and operational merit of adding a substantial volume of energy storage by 2045. PowerSimm also incorporated uncertainty in fuel prices that helped determine the economic merit of increased expansion of renewable generation in excess of the RPS standards. For example, the optimal mix of renewables for Oahu includes a 57% increase in forecasted utility solar introductions, a 21% increase in forecasted offshore wind introductions, and an optimized battery buildout plan that reaches 10,000 MWh by 2045. The results of PowerSimm’s optimization of renewables and batteries for Oahu are presented below in Figure 1.

![Projected Optimal Additional Renewables and Batteries for Minimum NPV - Oahu](image)

**Figure 1: Results of Ascend’s co-optimization of offshore wind, utility solar, and batteries for Oahu’s portfolio.**

Ascend also optimized the Post-April PSIP Plans for Maui and Hawaii. The optimal resource mix for Maui includes a 74% increase in utility solar, a 34% increase in onshore wind, and the addition of 2,400 MWh batteries. The optimal resource mix for Hawaii includes an 87% increase in forecasted onshore wind introductions, and an optimized battery buildout plan that reaches 180 MWh by 2045.

For each of the islands, Ascend compares the net present value (NPV) of total portfolio costs from the present to 2045 for the original Post-April PSIP Plan, the two E3 Plans, as well as two Ascend-developed Plans. The two Ascend-developed plans are: 1) Ascend’s optimization of the Post-April PSIP Plan with batteries (the Post-April PSIP Plan with Batteries), 2) Ascend’s optimization of the Post-April PSIP Plan with renewables and batteries (the Ascend Plan). Relative to the original Post-April PSIP Plans, the Post-April PSIP Plans with Batteries provide a 1%-3% reduction in NPV portfolio costs for the Companies, while the Ascend Plans provide a slightly larger reduction of 3-5% in NPV portfolio costs for the Companies.
PowerSimm also analyzed resource adequacy under conditions of increasing intermittent renewable penetration. PowerSimm’s analysis demonstrates that while intermittent renewables combined with batteries reduce the Companies’ need for thermal generation, they do not nullify this need. Utilizing its ability to capture a wide range of possible future conditions, PowerSimm shows that a significant level of thermal generation capacity will still be necessary to reliably meet load by 2045, when the Companies’ resource mix will be 100% renewable. Since there is always a possibility for extreme weather scenarios that severely reduce solar and wind generation, the Companies’ thermal fleet has to have sufficient capacity to make up for substantial losses in intermittent renewable generation in order to ensure future resource adequacy. Ascend assessed the Loss of Load Probability (LOLP), or the probability of outages due to load exceeding supply, for the plans. The results indicate that the Oahu E3 Plan and the Maui E3 Plan would not be able to maintain the security of the energy supply, leading to higher chances of power outages. Both the Oahu and Maui E3 Plans accelerate the retirement of thermal generators without providing sufficient updates to the thermal fleet. These results suggest that upgradations of the thermal fleet would be an essential component of a viable integrated resource plan.

The analysis of all the plans and their optimized derivations was conducted on an hourly scale. To gain more insight into the sub-hourly dynamics of the Companies’ power systems under conditions of higher renewable penetration, Ascend utilized PowerSimm’s System Flexibility Software. System Flexibility Software uses historical renewable generation data to evaluate at the minutely level the Companies’ flexible generation requirements (i.e. minutely, sub-hourly and hourly ramps and cycles) that accompany the integration of intermittent renewables. The results demonstrate that flexible generation requirements increase dramatically with the increasing levels of intermittent renewable generation, particularly with increasing solar. Batteries provide an excellent option for balancing out these sub-hourly and hourly fluctuations because of their ability to discharge energy precisely and extremely rapidly, with no additional production costs.

Ascend compared the costs of meeting these flexible generation requirements with batteries versus with conventional thermal generation. For this section, PowerSimm evaluates batteries that charge and discharge on an hourly scale (flexible batteries) and minutely scale (regulation batteries). Importantly, regulation batteries are not included in the optimized plans, which were developed and evaluated on an hourly-scale. The results support an introduction into Oahu’s system of flexibility batteries by 2022 and an immediate introduction of regulation batteries. The savings provided by these two types of battery grow over time with the higher renewable penetration rates.

In sum, through the analysis of the given resource plans and the development of the Ascend-optimized resource plans, this report provides insight into: (1) the benefits of flexible thermal generation with higher renewable penetration, (2) the benefits of load-shifting batteries with higher renewable penetration, (3) the necessity for substantial dispatchable generation in order to maintain resource adequacy in a system with higher levels of intermittent renewables, and (4) the benefits of serving regulation with batteries instead of with conventional thermal generation in a system with higher levels of intermittent renewables.

1. Background

This report’s objective is to evaluate the Companies’ Post-April PSIP Plans and E3’s optimization of these plans, as well as to optimize the original Post-April PSIP Plans through the utilization of Ascend’s PowerSimm model. In this report, Ascend will first provide PowerSimm’s evaluation of the Post-April PSIP Plans and E3 plans for each island system. Second, this report will go over the benefits of flexible thermal generation for Oahu, presenting the optimal introduction of flexible thermal units into Oahu’s thermal fleet. Third, this report will present PowerSimm’s analysis on resource adequacy for the plans, highlighting the need to maintain sufficient dispatchable generation capacity to ensure the security of supply under all weather conditions. Fourth, this report will present the details on the resource plans created by Ascend for each of the three island systems, comparing them to the non-Ascend resource plans discussed earlier in the report. Fifth, this report will detail the sub-hourly and hourly flexible generation requirements that accompany high levels of intermittent renewable penetration, and additionally show the benefits of utilizing batteries to address these flexible generation requirements.

For each of the three island systems, Ascend analyzes and compares four plans, two that were not developed by Ascend, and two that were developed by Ascend. For Oahu, Ascend evaluates an additional non-Ascend Plan. The plans not created by Ascend (i.e., the original Post-April PSIP Plan, the E3 Plan and the E3 Plan with LNG) will be reviewed in Section 2. The two plans developed by Ascend (i.e., the Post April PSIP Plan optimized with batteries, and the Post-April PSIP Plan optimized with both renewables and batteries) will reviewed in Section 4, and then compared to the three other plans. A summary of all the plans included in this report are provided in Table 2 below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Brief Description</th>
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<tbody>
<tr>
<td>Non-Ascend resource plans evaluated by Ascend (Detailed in Section 2)</td>
<td></td>
</tr>
<tr>
<td>Post-April PSIP Plan</td>
<td>Post-April PSIP Plan without modification</td>
</tr>
<tr>
<td>E3 Plan¹</td>
<td>Post-April PSIP plan optimized through E3’s RESOLVE model; no LNG</td>
</tr>
<tr>
<td>E3 Plan with LNG (only for Oahu)</td>
<td>Post-April PSIP plan optimized through E3’s RESOLVE model; with LNG</td>
</tr>
<tr>
<td>Ascend-developed resource plans (Detailed and compared with non-Ascend plans in Section 4)</td>
<td></td>
</tr>
<tr>
<td>Post-April PSIP Plan with Batteries²</td>
<td>Original Post-April PSIP plan with an Ascend-optimized battery buildout plan</td>
</tr>
<tr>
<td>Ascend Plan</td>
<td>Post-April PSIP plan with optimized levels of utility PV and offshore wind, and optimal battery buildout plan</td>
</tr>
</tbody>
</table>

Table 2: Plans included in this report.

Importantly, the Post-April PSIP Plans have slightly different assumptions in Section 2 and Section 4. As opposed to its “High” DGPV assumptions in the initial comparison with the E3 Plans in Section 2, the Post-April PSIP Plans in Section 4 contain lower, “Market” DGPV assumptions in the comparison with the Ascend-developed plans, which also use the Market DGPV assumptions. The E3 Plans evaluated in Section 2 and Section 4 are identical, containing High DGPV assumptions.

¹ In addition to the two plans, Ascend also evaluates the E3 Plan with LNG for Oahu.
² It is worth noting that the original Post-April PSIP Plans do include batteries, but at sub-optimal levels. Ascend uses the naming convention ‘Post April Plan with Batteries’ for the sake of expediency.
Additionally, the costs of the plans are calculated in a slightly different manner in Section 2 and Section 4. In Section 2 the total costs of the plans are calculated without DGPV costs, while in Section 4 they are calculated with DGPV costs included.

2. Validation of Post-April PSIP Plans and E3 Plans

Ascend used PowerSimm to evaluate the total net present value (NPV) of portfolio costs for the Post-April PSIP Plan and the E3 Plan with no LNG for each island system. Additionally, PowerSimm analyzed the NPV Portfolio costs of the Oahu E3 Plan with LNG.

According to PowerSimm’s results, the E3 Plan has an NPV Portfolio cost that is $193 M higher than the original Post-April PSIP Plan. The E3 Plan installs less renewable capacity than the Post-April PSIP Plan. In particular, the offshore wind capital costs for the E3 Plan is 45% less than the offshore wind capital costs for the Post-April-PSIP Plan. Thus more thermal generation must be utilized in the E3 plan, causing the E3 plan to have $602 M more in production costs than the Post-April PSIP Plan.

PowerSimm incorporates into its evaluation of NPV portfolio costs penalties for a resource plan’s expected shortfalls in meeting load under the Unserved Energy Cost category. For each MWh short, PowerSimm provides a penalty of $10,000. Since the Oahu E3 Plan falls short in meeting resource adequacy standards, its portfolio costs rise by $50 M with the inclusion of these penalties. The results of PowerSimm’s analysis of resource adequacy for the Oahu plans are discussed in section 4.3.1.

![Figure 2: NPV Portfolio Costs for the Oahu Post-April PSIP Plan and E3 Plans.](image-url)
Compared to the original Post-April PSIP Plan, the E3 Plan reduces portfolio costs by 11%, or $1,495 M. The lower fuel prices of LNG are the chief contributor to the lower NPV costs. LNG conversion reduces total production costs by $1,477 dollars. Additionally, since LNG fuel prices are less volatile, the risk premium, which monetizes the risk of fuel exceeding the mean of its forecasted price, decreases significantly for the E3 Plan with LNG.

![Figure 3: NPV Portfolio costs of the Maui Post-April PSIP Plan and E3 Plan.](image)

Relative to the Maui Post-April PSIP Plan, the Maui E3 Plan reduces portfolio costs by $301 M. For intermittent renewables, the E3 Plan’s capital costs are $94 M less than the Post April PSIP Plans’ capital costs. Even more striking is the reduction of $545 M in production costs provided by the E3 Plan. However, the Maui E3 Plan fails to meet resource adequacy standards to an even greater degree than the Oahu E3 Plan, which adds $382 M to its portfolio costs. PowerSimm’s analysis of resource adequacy for the Maui E3 Plan will be discussed in section 4.3.2.
Figure 4: NPV Portfolio Costs the Hawaii Post-April PSIP Plan and E3 Plan.

Compared to the Hawaii Post-April PSIP Plan, the Hawaii E3 Plan lowers NPV Portfolio costs by $91 M.

Though Ascend’s evaluation through PowerSimm and the Companies' evaluation through Plexos differ in their forecasted costs for the plans, the general trends of the results from the two models show a relative consistency. The table below shows the percent difference in total costs for each E3 Plan relative to the base Post-April PSIP Plan according to the two models.

<table>
<thead>
<tr>
<th>Percent difference in costs of E3 Plan relative to Post-April PSIP Plan with Plexos and PowerSimm</th>
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<tbody>
<tr>
<td><strong>Plexos Evaluation</strong></td>
</tr>
<tr>
<td>Oahu E3 Plan</td>
</tr>
<tr>
<td>Oahu E3 Plan with LNG</td>
</tr>
<tr>
<td>Maui E3 Plan</td>
</tr>
<tr>
<td>Hawaii E3 Plan</td>
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Table 3: Comparison of evaluation of plans by Plexos and PowerSimm
3. Flexible Thermal Generation

The transition to a high renewable energy portfolio paradoxically requires the restructuring Oahu’s thermal generation to a more flexible fleet. While at first blush one may see little merit in new thermal generation, this investment remains a critical component of the thermal transition to a 100% renewable portfolio. Even in 2045, variable meteorologies create conditions, which necessitate the use of thermal generation.

With high intermittent renewable penetration, the operating patterns of dispatchable generation alter significantly. Instead of providing power at steady rates throughout the day, thermal generation is expected to ramp up and down rapidly to address the imbalances between load and supply that comes from solar and wind generation’s volatility. This section will elucidate the need for flexible thermal generation. Then this section will present Ascend’s optimized additions to Oahu’s thermal fleet, as well as a comparison between PowerSimm’s calculations of the total costs for (1) Oahu’s existing thermal fleet with no updates, (2) Oahu’s Ascend-optimized flexible thermal fleet, and (3) the updated flexible thermal fleet contained in the Oahu Post-April PSIP Plan. Ascend will provide the total costs of these three thermal fleets under conditions of perfect and imperfect foresight.

3.1. The Need for Flexible Thermal Generation

Since the availability of wind and solar generation is contingent on weather patterns and their output is taken before thermal generation, the operating patterns of thermal generation have to undergo a shift in a system with high penetration rates of intermittent renewable generation. Thermal generation shifts from operating at base load to operating on a more flexible and irregular basis, serving load during the periods when wind and solar cannot provide sufficient generation to meet load.

Figure 5: Resource interaction for two-week period in May, 2025.

Figure 5 presents a typical example of thermal generation operations under Oahu’s growing levels of intermittent renewable penetration in 2025. Thermal generation is very low when solar generation peaks during the middle of the day and is thus able to serve the majority of load. Since, during solar’s off-peak hours, there is very little wind generation, thermal generation must ramp up to meet load, virtually serving all of load for the majority of the evening and night-time hours.
Under such operating conditions, having thermal generation units that are relatively inflexible can incur significant production costs. With higher intermittent renewable penetration, the production costs with an inflexible thermal fleet are higher than with a flexible fleet because inflexible generators, such as steam generators, will be required to come online to serve load for relatively short durations during peaking conditions. Steam units have long minimum-run times, usually around 12 hours. Thus, if additional thermal generation is only necessary for 4 hours, steam units will have to continue to run for 8 more hours at minimum generation. Since steam units run much more inefficiently at minimum generation than at maximum generation, production costs rise in such scenarios. On the other hand, a flexible thermal unit such as a combined cycle generator (CC) has a minimum run time of 1-hour. Thus, if additional thermal generation is only necessary for 4 hours, CCs can shut off immediately thereafter, incurring no additional costs.

**Figure 6: Dispatch Plan without 1x1 combined cycle generators, January, 2025.**

Figure 6 provides an example of rising production costs without flexible thermal generation. The most important aspect to note in this dispatch plan is the thermal generation of the Waiau steam units (shaded dark blue). On January 23rd, the Waiau units come online at approximately 5:00 p.m., when solar generation (shaded yellow) declines, in order to meet load. After 11:00 p.m. the Waiau units’ generation is no longer necessary to meet load, but, since they have a minimum run-time of 12 hours, they have to continue to run at minimum generation (5 MW per unit) until 5:00 am. At these must-run generation levels, the steam units operate at a relatively inefficient heat rate (21 MBtu/MWh) compared to when they operate at maximum capacity (10-11 MMBt/MWh). Thus, keeping these units running at minimum generation incurs significant costs.
Figure 7: Dispatch plan with 151 MW of 1x1 combined cycle generators, January, 2025.

Figure 7 shows the dispatch plan for the same week with 151 MW of 1x1 CCs included (shaded dark green). Compared to the plan without the CCs, the utilization rate of the Waiau steam units drops considerably. The Waiau steam units do come online for peaking hours, but less of them do; thus they incur less heat rate penalties. Moreover, the CCs displace the generation of the Waiau combustion turbine (CT) generator (represented by the light green sliver above the Waiau steam units) during peak conditions, as they are more efficient than CTs in providing flexible generation.

In sum, there is a compelling need to have a more flexible fleet to address the imbalance between supply and load that comes with high intermittent renewable penetration. Without the flexible thermal fleet, production costs will be significantly higher because a considerable amount of steam generators will be compelled to come online for a relatively short duration during peaking conditions, and then remain running at minimum generation for a substantial block of hours when their generation is no longer necessary.

3.2. Optimal Thermal Generation Mix

Figure 8 compares the total costs for thermal generation of three thermal mixes for Oahu: (1) the optimized thermal mix plan developed by Ascend, (2) a thermal mix that does not upgrade Oahu’s thermal fleet, (3) the Post-April PSIP Plan thermal mix. Ascend’s optimal thermal mix calls for the addition of 1 CC in 2025, 1 internal combustion engine (ICE) in 2025, 2 ICES in 2026, 1 CC in 2027, 1 ICE in 2030, and 1 ICE in 2035. The Oahu Post-April PSIP Plan adds 5 151 MW CCs in 2025, 2027, 2030, 2032, and 2035 respectively. The CC capacities are 151 MW, while the ICE capacities are 16.8 MW.
The lower bar in each plan represents the total production costs of each thermal mix. Since there are additions to the thermal fleet in both the Post-April PSIP Plan thermal mix and the Ascend thermal mix, the capital costs for those additions are included as well in the total costs, as indicated by the light green bar stacked on top of production costs. Ascend also analyzed the level of resource adequacy provided by each of these thermal mixes, and though the thermal mix without upgrades (represented by the middle bar) has no capital costs, such a thermal mix fails to meet resource adequacy standards, placing Oahu at substantial risk for power outages. Thus, penalties of $10,000 per forecasted MWh short were added to the total costs. Relative to the thermal mix with no upgrades to the fleet, the Ascend thermal mix provides $342 M less in total costs, while Post-April PSIP Plan’s thermal mix provides $69 M less in total costs.

3.3. Introducing Imperfect Foresight

The thermal generation costs presented in the prior section were calculated under conditions of perfect foresight. Perfect foresight entails that the production cost model can see the future states of load, solar generation and wind generation, and decide accordingly how to employ thermal generation units. In reality, however, operators do not have this information; thus, to be prepared for any sudden drops in renewable generation or spikes in load, operators tend to leave thermal generators online at minimum generation for longer stretches. PowerSimm’s modeling of imperfect foresight accounts for such operating practices. Figure 9 below compares the results of each thermal mix with perfect and imperfect foresight.
Figure 9: Total costs for flexible and inflexible thermal fleets with perfect and imperfect foresight.

With imperfect foresight, costs increased by the greatest percentage for the thermal mix with no upgrades. The thermal fleet without any introduction of ICES or CCs incurs the most additional costs with imperfect foresight because its relatively inflexible generators must stay online at minimum generation for longer periods of time. On the other hand, the flexible fleets are able to start up and shut down, and ramp up and ramp down at much faster rates, enabling them to run at more efficient heat rates under conditions of imperfect foresight.

Ascend’s optimal thermal mix has a smaller increase in costs with imperfect foresight (2.6%) compared with the Post-April PSIP Plan’s thermal mix (3.2%). Ascend’s optimal thermal mix contains two CCs and 5 ICES, while the Post-April PSIP Plan’s mix contains 5 CCs. ICES are the more flexible generator; thus the prevalence of them in Ascend’s fleet causes the lower increase in costs with imperfect foresight.

4. Ascend-Developed Plans and Final Comparisons of Each Island’s Plans
To update and improve upon the three Post-April PSIP Plans, Ascend used PowerSimm to develop new, optimized plans. In the new plans developed by Ascend, one of the main features is the inclusion of load-shifting batteries. Thus, this section will first demonstrate the benefits of including load-shifting batteries in energy portfolios with high levels of renewables. Second, this section will discuss resource adequacy, highlighting the need to maintain adequate thermal reserves in the case of an extreme event. Third, this section will present the details of PowerSimm’s analysis of the Ascend-developed plans for each island system, as well as a comparison of these plans to the non-Ascend plans.

4.1. Load-Shifting Batteries
One of the main challenges of shifting to a 100% renewable portfolio is the intermittent nature of renewable generation. For instance, a renewable portfolio with a large amount of solar will generate
excess power during the day, but too little at night. Load-shifting batteries provide a means to store that excess day-time generation and discharge the power at night. In this way, when shifting to a 100% renewable portfolio, batteries become a crucial and cost-effective tool for meeting load. This subsection will further elucidate the advantages of utilizing load-shifting batteries; then it will present the assumptions Ascend made regarding the inclusion of load-shifting batteries in the PowerSimm model.

4.1.1. The Case for Batteries

To demonstrate the advantages of including load-shifting batteries in portfolios with a large percentage of renewables, the following figures show PowerSimm simulation results of battery charge/discharge cycles in relation to customer load, renewable generation, and thermal generation for two different time periods for a single stochastic simulation. These two time periods were specifically chosen to demonstrate times when there are sufficient renewables and battery capacity to minimize the need for thermal generation. However, even at these levels of renewables and batteries, there are still times when there is insufficient renewable energy (due to, for example, extended periods of light winds or cloudy weather) to eliminate the need for thermal generation.

Figure 10 shows a time (May 2045) when there is more than adequate renewable generation. In this figure, there are prolonged periods where renewable generation far exceeds the customer load. During these times, batteries can be charged to minimize dump energy. However, once the batteries reach their capacity, charging stops and any additional renewable energy is “dumped”, or not utilized. PowerSimm modeling recognizes that capturing all dump energy is not the optimal solution. Building excessive battery capacity at some point will cost more than the value of the energy it is designed to store.

![Figure 10: One stochastic simulation for a two-week May 2045 with 7,000 MWh batteries.](image)

If it were not for the load-shifting batteries added to this portfolio, a significant amount of the energy generated by solar renewables during the day would be wasted since there would be no mechanism to store this energy. Moreover, the stored energy is then utilized when solar generation is not sufficient to meet load. This is indicated in Figure 10 when the battery charge is negative, that is, discharging its stored
energy in order to meet net-load. Without load-shifting batteries, there would be insufficient renewable energy resources whenever solar stops generating at night, thus requiring thermal generation to meet customer demand. Not only would this thermal generation in 2045 require burning expensive biofuels, but it would also require expensive plant startups or running power plants at a sub-optimal generation level to prevent startups and shutdowns.

Figure 11: Comparison of battery dynamics for May 6th and 7th, 2045. The diagram to the left indicates the battery state of charge. The diagram to the right indicates the resource interactions between renewable energy (yellow line), customer load (red dashed line), thermal generation (black line) and batteries (blue line).

Figure 11 provides a more in-depth look at battery dynamics on May 5th and 6th, 2045. As seen in the right diagram, renewable generation is very low from midnight to sunrise on May 6th; thus the battery has to discharge. In the left diagram, the battery discharge is presented by the decreasing slope, indicating that the battery discharged around 3,000 MW. When solar generation begins to exceed customer load at approximately 10:00 a.m. (see right diagram), the battery starts to charge up to its full capacity of 8,000 MWh. There is more wind generation during the night of the 6th and 7th than the prior night. Thus the battery has to discharge relatively little of its stored energy, and even before sunrise it begins to recharge to full capacity. As a result, when solar generation comes online on May 7th, the battery absorbs only a minimal amount of the generation in excess of load, and then ceases to charge during the period in which solar generates the most dump energy. The left diagram confirms that the battery barely charges because it is already at full capacity.

Figure 12 shows the resource interactions between thermal generation, renewables, and batteries in a winter month (January, 2045). When renewable generation exceeds load, batteries are able to absorb the excess energy by charging. When renewable generation is less than load, batteries can help meet load by discharging. However, there are periods when batteries are totally depleted and thermal generation must ramp up to meet load. These scenarios are typically attributable to weather conditions that are either cloudy (minimal solar generation) or still (minimal wind generation). During such time periods, biodiesel must be consumed to provide adequate generation to meet load.
Figure 12: One stochastic simulation for January 2045 with 8,000 MWh batteries.

Figure 13 provides a more detailed view of the dynamics between renewables, batteries and thermal generation for January 24th and 25th, 2045. On January 24th, there is not enough solar generation to meet load, and very little wind generation during the night. Thus the load-shifting battery must discharge the rest of its stored energy early in the day, and thermal generation must come online, eventually serving over 80% of the load during the night of the 24th and 25th. However, during the day of the 25th, renewables exceed customer load, enabling batteries to charge.

Figure 13: Comparison of battery dynamics for January 24th and 25th, 2045. The diagram to the left indicates the battery state of charge. The diagram to the right indicates the resource interactions between renewable energy (yellow line), customer load (red dashed line), thermal generation (black line) and batteries (blue line).

Thus, by 2045 load-shifting batteries do not eliminate thermal generation, but they do minimize the need for it. Thermal generation will be especially crucial during extended periods of low renewable generation.
(e.g. during a series of cloudy days where batteries are not able to recharge with adequate solar generation). Moreover, even during periods where there is sufficient renewable generation to meet load, thermal generation is always running at a steady, though minimal level. To economically meet the thermal generation requirements under conditions of higher intermittent renewable penetration, Oahu would have to (1) update its existing thermal fleet with flexible thermal units, as detailed earlier in section 3, and (2) maintain sufficient thermal generation capacity in order to ensure resource adequacy. This second component will be gone over in section 4.3.

Load-shifting batteries provide a cost-effective way to smooth over the variability of intermittent renewable generation by storing excess energy, also referred to as dump energy, that would otherwise be lost. Below, Figure 14 addresses this point directly by showing the amount of dump energy per year with and without batteries. The Oahu Post-April PSIP Plan optimized with batteries reduces dump energy by approximately 120 GWh in 2025, and by over 400 GWh in 2040.

![Dump Energy Reduction Using Optimal Batteries](image)

**Figure 14: Dump energy for the Oahu Post-April PSIP Plan without batteries vs. with batteries**

To summarize, the inclusion of load-shifting batteries in portfolios with high levels of renewables has substantial advantages. Load-shifting batteries can store large amounts of excess renewable energy generated during the day (dump energy that would otherwise be lost) and discharge that energy to meet load at times when renewable generation cannot meet load. However, though load-shifting batteries mitigate the need for thermal generation, they do not entirely eradicate this need.

### 4.1.2. Battery Assumptions

While including batteries in the PowerSimm modeling framework, Ascend made a series of assumptions about load-shifting batteries. First, Ascend assumed a 15-year lifetime for load-shifting batteries. Second, because batteries can be refurbished, Ascend assumed that the value of a battery at the end of its lifetime is 50% of the install cost at that time. Third, assuming an 8% interest rate and that battery installation costs from 2045 and beyond remain unchanged at $306/KWh, Ascend calculated the effective installation cost as follows:
\[ EIC_t = IC_t - \frac{1}{2} PV(IC_{t+15}^{15\%}) \]

Where EIC is the effective installation cost for a particular year, IC is the installation cost for a particular year, and PV is the present value function in Excel. Using this method, Ascend calculated the effective installation cost (EIC) for each year using battery installation costs (IC) provided by the Companies in the April 2016 PSIP filing. These costs for each year are shown in Table 4 below:

<table>
<thead>
<tr>
<th>Year</th>
<th>Install Cost ($/KWh)</th>
<th>Effective Install Cost ($/KWh)</th>
<th>Year</th>
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<tr>
<td>2030</td>
<td>349</td>
<td>301</td>
<td>2045</td>
<td>306</td>
<td>258</td>
</tr>
</tbody>
</table>

Table 4: Cost and Effective Cost of battery installation by year

Ascend also assumed that, to prevent damage from occurring, load-shifting batteries will never discharge below 20% of their capacity. To account for this assumption, there was a 20% adder included in the capital costs of batteries. However, it is important to note that the battery buildout plans shown in the following subsections show the functional battery capacity, that is, the battery capacity that can fully discharge. The actual battery capacities, which determine the capital costs, are always 20% greater than the functional battery capacities, which are shown in the figures below.

All of these battery assumptions were used across all new plans that include load-shifting batteries.

4.2. Marginal Renewable Resource Analysis

PowerSimm was also used to conduct a marginal analysis of an additional MW of renewable generation for the Oahu Post-April PSIP Plan. For these calculations, 1 MW of renewable generation was added to the Oahu portfolio to determine the effective cost of the additional power from each 1 MW addition. The resulting levelized cost of power (i.e. cost of power inclusive of both variable and capital costs over the lifetime of the generation unit) was then compared to the levelized cost of power from traditional thermal generation assets available in the Oahu portfolio. The results from this analysis are shown in Figure 15.
Figure 15: Compares levelized cost of different types of generation with and without batteries

Figure 15 shows that renewables become more cost-effective early on relative to the variable cost of thermal generation, excluding all fixed costs. Load-shifting batteries combined with solar start adding significant value in 2025, by capturing dump renewable generation and serving to reduce the cycle demand on thermal generation. Load-shifting batteries combined with wind generation begin to add value by 2030, when offshore wind generation comes online. That being said, load-shifting batteries only account for battery benefits on an hourly scale. On the other hand, regulation batteries, which incorporate battery usage on a minutely scale, provide cost savings much earlier on. By 2035, adding renewables without adding battery capacity for storage does not make economic sense, especially for solar. Large differences upwards of $100 per MWh can be realized by simply adding sufficient battery storage along with solar. Thus the ability of Oahu to realize high renewable generation rates become a function of battery costs continuing to decline.

Additionally, Figure 15 shows that solar combined with batteries and wind combined batteries provide similar costs through time. Ascend's analysis has solar becoming slightly cheaper than wind after 2030; yet which resource will actually provide cheaper power in the future is an open question. If there is a steeper decline in the costs of offshore wind, then it could be more cost-effective to opt for further wind generation, diminishing to some extent the need for batteries, as a MW of wind generation requires about half the storage level as a MW of solar generation. If there is a steeper decline in the costs for batteries, the combination of solar generation and batteries would become even more appealing.

4.3. Resource Adequacy
Due to the intermittency of renewable resources, there is always the potential for extended periods of still and/or cloudy weather that severely curtails solar and wind generation. Under such extreme weather

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3 See section 5.2.2 for more on regulation batteries.
conditions, the energy system has to be able to continue to meet load reliably. Central to maintaining resource adequacy under all weather conditions is recourse to sufficient dispatchable generation capacity.

This section will present probability distributions of thermal generation in 2045, as produced over numerous weather simulations, for both the Oahu Post-April PSIP Plan and the Oahu Post-April PSIP Plan with Batteries. Then, this section will assess the Loss of Load Probability (LOLP) (i.e. the probability of outages due to load exceeding supply) for both Oahu and Maui under the Post-April PSIP Plan, the Ascend Plan, and the E3 Plan.

Figure 16 displays the probability distribution of thermal generation in 2045 under the Oahu Post-April PSIP Plan.

![Thermal Generation Cumulative Probability Distribution](image)

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*Figure 16: Probability distribution of thermal generation requirements over distinct weather simulations for the Oahu Post-April PSIP Plan (without optimized batteries).*

In 2045, the amount of thermal generation most often required (i.e. the mode) is forecasted to be 68.5 MW. There is, however, also 1% chance in 2045 that Oahu will confront weather conditions requiring 924 MW of thermal generation, and the maximum amount generation Oahu will be expected to serve is 1182 MW, which is 116% of average load for the year. Such extreme scenarios are outliers, but nevertheless Oahu would have to be prepared to meet such scenarios.
As Figure 17 shows, the addition of 7000 MWh of batteries to the Oahu Post-April PSIP Plan shifts the probability distribution of thermal generation to lower values. With 7000 MWh of batteries, the average amount of thermal generation required in 2045 drops by 68%, from 260 MW to 84.4 MW. The maximum thermal generation required also shrinks from 1182 MW to 947 MW. However, compared to the shrinkage in the average amount of thermal generation required (68%), the reduction in the maximum amount of thermal generation required is not as dramatic (20%). The limited reduction of maximum thermal generation under the Post-April PSIP Plan with Batteries alludes to the limitations of batteries in extreme weather scenarios. If there is an extended weather period with extremely low wind and solar generation, batteries would be unable to recharge from renewable sources. If batteries were to charge, they would do so from thermal generation in excess of load. Thus in such scenarios sufficient thermal reserves would have to be in place to serve the overwhelming majority of load.

Figure 18 and

Figure 19 further emphasize the variability of thermal generation requirements. Ascend ran 20 simulations of thermal generation requirements over a two-week period in May, 2045. Figure 18

Figure 19 display the 5th percentile, average, and 95th percentile of the forecasted amount of thermal generation required for the Oahu Post-April Plan and the Oahu Post-April Plan with Batteries (7000 MWh) respectively.
Figure 18: Thermal generation distribution over distinct weather simulations for two-week period in May, 2045 for the Oahu Post-April PSIP Plan (without optimized batteries).

Figure 19: Thermal generation distribution over distinct weather simulations for two-week period in May, 2045 for the Oahu Post-April PSIP Plan optimized with 7000 MWh of batteries.

The blue line signifies the average thermal generation requirements when accounting for all the weather scenarios analyzed. The orange P5 line represents the mild weather scenarios that are more favorable to renewable generation (i.e., 5% of the scenarios evaluated have less thermal generation required). The gray P95 line represents extreme weather scenarios that are unfavorable to renewable generation (i.e., 95% of the scenarios examined require less thermal generation). A comparison of Figure 18 and

Figure 19 reveals that batteries substantially reduce the amount of additional thermal generation. Without batteries, large amounts of thermal generation are required on a daily basis, irrespective of the...
weather scenario. On the other hand, with 7000 MWh of batteries, the average amount of thermal generation required remains for the majority of the time around 68.5 MW.

Nevertheless, though the need for a significant amount of thermal generation is curtailed by batteries, there are still extreme weather scenarios to be found in May 2045 where the majority of load will have to be served by thermal generation. In Figure 19, the gray P95 line represents these scenarios, spiking up to 750 MW in some instances.

Figure 20 shows that in a winter month such as January the potential for such spikes in thermal generation increases in frequency and magnitude. For this two-week period in January 2045, there are 5 instances where the extremes scenarios require thermal generation to ramp up to 500 MWh or more, compared to the two-week period in May 2045 found in Figure 19, where there were only 2 such instances. The increase in the frequency and magnitude of price spikes follows from the variability in solar generation during winter months.

![Thermal Generation Distribution - P Stats](image)

**Figure 20**: Thermal generation distribution over distinct weather simulation for two-week period in January, 2045 for the Oahu Post-April PSIP Plan optimized with 7000 MWh of batteries.

In sum, even with high levels of wind and solar generation, Oahu must maintain thermal generation capacity at levels where it can serve the majority of load in order to maintain resource adequacy. Even if thermal generation is rarely utilized at high capacities, the guarantee of dispatchable energy in periods with low intermittent renewable generation is essential for meeting load reliably. Though load-shifting batteries significantly curtail the need for thermal generation, they do not completely eliminate this need.

### 4.3.1. Loss of Load Probability: Oahu

Loss of Load Probability (LOLP) or Loss of Load Expectation (LOLE) calculates the expected duration of outages and the expected shortfall in generation per year given a system’s available resource capacity and forecasted load. LOLP provides an important indicator of a system’s level of resource adequacy.

Ascend assessed LOLP for the Oahu Post-April PSIP Plan, Ascend Plan, and E3 Plan. To measure LOLP, Ascend calculated under each plan the expected Loss of Load Hours (LOLH) per year, i.e., the amount of hours when load exceeds supply. Ascend also calculated the shortfall of MW per year. The LOLP analysis
uses an advanced integrated simulation framework that captures the joint probability of load and intermittent renewable generation over numerous simulated weather conditions. Because Ascend applies an integrated simulation framework of renewables, load and thermal generation outages, resource deficits can be examined at the 5th, mean and 95th.

NERC’s reliability standard for planning in a large integrated power grid is an LOLH of 2.4 hours per year, which corresponds with a total of 24 hours of outages over 10 years.

**Loss of Load Hours**

![Loss of Load Hours Graphs](image)

*Figure 21: Loss of load hours from 2017 to 2045 for the Oahu Post-April PSIP Plan, Ascend Plan, and E3 Plan.*

Figure 21 presents a comparison of the Loss of Load Hours for Oahu under the Post-April PSIP Plan, the Ascend Plan, and the E3 Plan. The mean represents the average hours of outages per year from all the simulations examined. The confidence interval specified by the P5 and P95 endpoints indicate the range of possible hours the portfolio could be short in a given year with a 90% confidence that the true value is within this range.

For the Oahu Post-April PSIP Plan, the average LOLH never exceeds 2.4 hours. However, the P95th bound indicates 3 hours for 2028 and 7.5 hours for 2029 where load exceeds capacity. The increase in expected LOLH results from the retirement of the Kahe 5 and 6 units in 2028. With the introduction of offshore wind in 2030, the LOLH drops to 0 hours from 2030 onwards.

For the Oahu Ascend Plan, the LOLH is relatively similar to the Post-April Plan through 2020. After 2020, however, the Ascend Plan has no expected LOLH. The Ascend Plan adds significantly more renewable
generation and batteries than the Post-April PSIP Plan, placing Oahu in a better position to ensure a reliable power supply.

Out of all the plans evaluated, the Oahu E3 Plan has the lowest degree of resource adequacy. From 2017 to 2045 the mean LOLH exceeds 2.4 hours for 40% of the years, and the P95th exceeds 2.4 hours for 96% of the years. The E3 Plan assumes that all steam units will be retired by 2022, and the only update of the thermal fleet contained in the plan is in 2045. The E3 Plan calls for significant levels of batteries, which does assist in providing a secure supply; yet batteries cannot make up for such low levels of thermal generation, which undermine Oahu’s ability to furnish enough capacity to meet load under all conditions.

MWs Short

Figure 22: MWs short for Oahu’s Post-April PSIP Plan, Ascend Plan, and E3 Plan.

Figure 22 indicates resource adequacy by displaying the expected shortfall of MW per year for each plan. For the Oahu Post-April PSIP Plan, from 2017 to 2019 and from 2028 to 2030 the 95th confidence bound for the shortfall in generation reaches 150 MW, while for the rest of the years there is no or only a negligible expected shortfall in generation. For the Oahu Ascend Plan, from 2020 onwards there is no expected shortfall in generation. For the Oahu E3 Plan, there are no years evaluated without expected shortages. The Oahu E3 Plan’s highest mean value for MWs short over the years is 213 MW, which is over 4 times higher than the highest mean values for the Post-April PSIP Plan and the Ascend Plan.

Thus the LOLP results further bolster the conclusion that Oahu will continue to need thermal generation to serve load reliably. A plan such as the Oahu E3 Plan, which proposes early retirement of steam units and no significant updates of the thermal fleet, falls short in providing the necessary resource capacity to maintain the security of the power supply.
4.3.2. Loss of Load Probability: Maui

PowerSimm’s analysis of the Maui Post-April PSIP Plan and the Maui Ascend Plan found no expected loss of load from 2017 to 2045 for these two plans. PowerSimm’s analysis of the Maui E3 Plan, however, reveals the plan to fall short in meeting resource adequacy standards by considerable margins.

As shown in Figure 23 and Figure 24, the E3 Plan’s average LOLH over the weather simulations examined ranges from 22 hours to 36 hours from 2020 onwards. Correspondingly, the E3 Plan’s mean shortfall in MWs range from 150 MW to 170 MW from 2020 to 2045.

The E3 Plan’s drastic increase in LOLH and MWs short in 2020 has two chief causes. Firstly, relative to the Maui Post-April PSIP Plan, the E3 Plan installs 75 MW less of solar capacity and 10 MW less of onshore wind capacity in 2020. Secondly, the E3 Plan retires the 106 MW Maalea CC plant in 2022. The Maalea plant is Maui’s primary oil-based generation unit, and retiring this unit puts Maui in a position with very little thermal reserves, causing the island to be heavily dependent on renewable based generation. Thus, under weather conditions unfavorable to renewable generation, the Maui E3 Plan risks significant shortages.

4.4. Oahu Results and Optimized Plans

This subsection will detail the two new plans created by Ascend, the Post-April PSIP Plan with Batteries and the Ascend Plan. The Oahu Post-April PSIP Plan with Batteries was developed by optimizing the levels of batteries in the original plan. The Oahu Ascend Plan was developed by jointly optimizing solar generation, wind generation and batteries in the Post-April PSIP Plan. The end of this subsection will provide a comparison of the NPV portfolio costs of the two Ascend-optimized plans, as well as the Post-April PSIP Plan and the E3 Plan.
4.4.1. The Optimization of Batteries: Post-April PSIP Plan with Batteries

This plan is based on Oahu’s Post-April PSIP Plan, from which Ascend has developed an optimized battery buildout plan for load-shifting batteries. The optimized battery buildout plan is indicated by the dashed green line in Figure 25 below.

![Oahu Incremental Battery Buildout Plan (Optimal vs. Sub-Optimal)](image)

**Figure 25: Comparison of two suboptimal battery buildout plans with optimal buildout plan for the Oahu Post-April PSIP Plan.**

In Figure 25, three battery buildout plans are presented: the optimal plan, a plan with an over-installation of batteries and a plan with an under-installation of batteries. The dashed lines signify the battery capacity, while the solid lines signify the savings provided by each plan. Beginning in 2032, savings offered by the optimal plan grows steadily. In 2036, while the cost saved by the optimal buildout plan is around $100 M, the cost saved by the two suboptimal plans, which have lines stacked on top of each, are negligible. A comparison between the optimal installation of batteries and sub-optimal under-installation of batteries illustrates that by installing 1000 MWh less of battery capacity, savings drop drastically.
Figure 26: Battery Payoff Diagram for the Oahu Post-April PSIP Plan.

Figure 26 illustrates that additional battery capacity maintains positive marginal economic effectiveness until 7000 MWh. Beyond a capacity of 7000 MWh, the decreasing effectiveness of additional battery capacity in capturing additional dump energy causes savings to decrease.

4.4.2. The Optimization of Renewables and Batteries: The Ascend Plan
Ascend utilized the PowerSimm software to evaluate the concurrent changes needed to jointly optimize solar, wind, and batteries to come up with the renewable plus battery additions that would minimize the overall NPV of the selected portfolio. Sufficient PowerSimm analyses were performed to ensure the optimal mix of solar, wind, and batteries was identified. The existing renewable forecasts from the Oahu Post-April PSIP plan were designated as a starting point to determine how much additional wind, and solar, with corresponding battery storage, would be warranted to minimize overall theme costs.

Figure 27 displays the results from the co-optimization process that Ascend carried out to find the combination of offshore wind, utility solar, and batteries that minimize the NPV of Oahu’s portfolio costs.
As shown in Figure 27, the “sweet spot” in the renewable plus battery additions was determined by analyzing a host of paths towards the 100% renewable goal by 2045. This “sweet spot” corresponds to the acceleration of the Post-April PSIP Plan utility PV buildout by 57% and the offshore wind buildout by 21%, in addition to an optimized battery buildout plan. This combination, which is Ascend’s optimized plan, results in a NPV reduction of $809 M. It is important to note that to realize this optimal renewable plan, the addition of load-shifting batteries is required. Without batteries, as discussed earlier in this report, far too much energy is dumped at times of peak renewable generation, and far too little energy is available during the evening when solar renewables stop generating. Thus, accelerating the introduction of renewables goes hand in hand with the incorporation of load-shifting batteries. If batteries are not included in the plan, the additional renewable generation will actually substantially increase the NPV of Oahu’s portfolio costs. With this in mind, the optimal battery buildout plan for the Ascend Plan is displayed below.
Figure 28: Battery buildout plan for the Oahu Ascend Plan. Battery capacities on the figure do not reflect the additional 20% required to prevent battery damage.

Compared to the Oahu Post-April PSIP Plan with Batteries, the Oahu Ascend Plan has a more aggressive battery buildout plan, calling for 3,000 MWh of battery capacity more than the Oahu Post-April PSIP Plan with Batteries. The higher level of renewables introduced by the Ascend Plan render higher battery capacity levels more economical.

Figure 29: Comparison of renewable generation capacity between the Oahu Post-April PSIP Plan and the Oahu Ascend Plan.

Figure 29 presents the renewable additions of the Ascend Plan relative to the Post-April PSIP Plan. The Ascend Plan contains a 57% increase in utility solar and 21% increase in offshore wind. The marked additions of intermittent renewable generation in the optimized plan stem from the utilization of
batteries. Batteries are crucial in rendering the additional intermittent renewable capacity economically beneficial. Solar generation, in particular, has a concentration effect during hours when the sun is shining most directly, resulting in significant amounts of excess energy, off which batteries are able to capitalize.

Figure 30: Comparison of the Oahu Post-April PSIP Plan and the Oahu Ascend Plan by resource.

Figure 30 provides a comparison over time of the distinct types of resource generation contained in the Post-April PSIP Plan and the Ascend Plan. The generation from the installed resource capacities for the Post-April PSIP Plan are represented by the bars, while the generation from the installed resource capacities for the Ascend Plan are represented by the shaded areas behind the bars. The two plans start off with identical levels of resource generation. However, by 2020 the overall generation of the Ascend Plan begins to exceed the total generation of the Post-April PSIP Plan, due largely to the accelerated growth of solar generation and the introduction of batteries. With the accelerated growth of solar generation and batteries, the amount oil-based generation by 2032 is two and half times smaller for the Ascend Plan than the Post-April PSIP Plan. By 2040, with additional installations of wind for the Ascend Plan, the amount oil-based generation for the Ascend Plan is nearly three times less than the oil-based generation in the Post-April PSIP Plan.
Figure 31 shows, adding an optimized battery buildout plan to the Post-April PSIP Plan results in a $443 M reduction in Oahu’s NPV of portfolio costs from the original Post-April PSIP Plan. Ascend’s optimization of both batteries and renewables, yielding the Ascend Plan, occasions a $809 M reduction in portfolio costs. On the other hand, the E3 Plan increases NPV portfolio costs by $587 M. The increase in costs relative to the original Post-April PSIP Plan results from the lack of development of flexible thermal generation, which causes the E3 Plan to have the highest production costs out of the four plans examined, and incur a $50 M penalty for its nonfulfillment of resource adequacy standards.

4.5. Maui Results and Optimized Plans

In this subsection, Ascend evaluates the Maui Post-April PSIP Plan with Batteries, and then the Maui Ascend Plan. At the end of this subsection, Ascend compares the two Ascend-developed plans with the original Post-April PSIP Plan and the E3 plan.

4.5.1. The Optimization of Batteries: Post-April PSIP Plan with Batteries

The Maui Post-April PSIP Plan with Batteries was created through PowerSimm’s optimization of batteries for the original Post-April PSIP Plan. The optimal battery buildout plan is depicted in Figure 32 below.
Figure 32: Battery buildout plan for the Maui Post-April PSIP Plan with Batteries.

The black line denotes battery capacity over the years; the green line represents the costs without batteries; and the orange line represents the costs with batteries. It is interesting to note that the production costs drop considerably by 2020. The installation of solar and onshore wind in the Maui Post-April PSIP Plan causes this drop in costs. After the installation of solar and wind, batteries begin to be built out by 2021. Load-shifting batteries begin to provide a notable level of savings by 2032.

Figure 33: Cumulative probability distribution of thermal generation over distinct weather simulations for the Maui Post-April PSIP Plan (without batteries) in 2045.
4.5.2. The Optimization of Renewables and Batteries: The Ascend Plan

Ascend jointly optimized solar, wind and batteries to determine the resource plan that would provide the lowest portfolio costs for Maui. Due to the small size of the island, Ascend constrained the optimization of renewables to 100% of its present generation capacity. The results from this co-optimization process of renewables and batteries is presented in Figure 35 below.
Figure 35: Results of Ascend’s co-optimization of offshore wind, utility solar, and batteries for Maui.

Figure 35 illustrates that the mix of renewables and batteries that provided the lowest NPV costs corresponds to, relative to the original Maui Post-April PSIP Plan, a total additional installation of 74% of utility solar and a total additional installation of 34% of onshore wind. Furthermore, Figure 35 conveys that without optimal levels of batteries additional renewables, instead of providing a reduction in costs, generate an increase in production costs.

Figure 36 shows the battery buildout plan under the Maui Ascend Plan, further highlighting the production cost savings that optimal batteries provide.
The battery capacity for the Maui Ascend Plan exceeds the 2045 battery capacity of the Post-April PSIP Plan with batteries by 2026, and by 2045 the former plan's battery capacity is approximately three times higher than the latter. The production cost savings decrease significantly, as the increased renewable capacity makes greater use of the economic potential of batteries.
Figure 36 illustrates the capacity additions to the Maui Post-April PSIP Plan that generates the optimal Maui Ascend Plan. The base assumption of the Post-April PSIP Plan consists of one-time additions in 2020 of 80 MW of solar and 90 MW of onshore wind. Ascend’s optimized plan introduces an additional 30 MW of solar and wind in 2020, and continues to gradually increase renewable capacities over time. The MauiAscend Plan does not, as in the case of the Oahu Ascend Plan, increase renewables at the same rate each year. For Maui, seventy-four percent additional solar and 34% additional onshore wind capacities over the entire study timeframe, i.e. from 2017 to 2045, provide the least cost plan, when combined with optimal levels of batteries.

![Figure 36: Comparison of NPV of Maui Portfolio costs for the Post-April PSIP Plan, the Post-April PSIP Plan with Batteries, the Ascend Plan, and the E3 Plan.](image)

When the Post-April PSIP Plan is optimized with batteries, Maui portfolio costs decrease by $43 M, while when PowerSimm optimizes the Plan with batteries and renewables, portfolio costs decline by $81 M. The E3 Plan provides dramatically lower NPV costs when penalties for unserved energy are not included. However, due to the E3 Plan’s failure to meet resource adequacy standards, as presented in section 4.3.2., PowerSimm adds an additional $382 M in portfolio costs to the plan, bringing the NPV portfolio costs to $2,332 M, or $79 M less than the Post-April PSIP Plan.

4.6. Hawaii Results and Optimized Plans
In this section, Ascend analyzes the Hawaii Post-April PSIP Plan and its optimized counterparts. Due to favorable wind conditions on the Big Island, virtually all of its renewable generation installations are of onshore wind. Thus Hawaii provides an interesting study of the potential savings provided when batteries
are coupled with on-shore wind generation. In this subsection Ascend analyzes the Hawaii Post-April PSIP Plan optimized with load-shifting batteries (the Post-April PSIP Plan with Batteries), and then the Hawaii Post-April PSIP Plan optimized with batteries and renewables (the Ascend Plan).

4.6.1. The Optimization of Batteries: Post-April PSIP Plan with Batteries

Hawaii’s Ascend-optimized battery buildout plan is shown in Figure 39 below. By 2045, the battery capacity is 135 MWh, which is significantly more than the 15 MWh of batteries that the original Hawaii Post-April PSIP Plan proposes. The reduction in costs provided by batteries, however, is minimal. Wind generation and DGPV at the Post-April PSIP Plan’s levels do not reap substantial savings from battery utilization.

![Hawaii Battery Optimization Battery Buildout Plan](image)

*Figure 39: Battery buildout plan for HELCO’s Post-April PSIP Plan with Batteries.*

Figure 40 and Figure 41 provide a comparison of the cumulative probability distribution of thermal generation requirements for Hawaii in 2045 with and without optimized batteries. For the Post-April PSIP Plan with Batteries, the average thermal generation for 2045 decreases by 37% and the P95th by 15%. However, as in the case of Maui, the maximum thermal generation required to ensure security of supply for the most extreme weather scenarios stays the same between the plans with and without batteries.
Figure 40: Cumulative probability distribution of thermal generation over distinct weather simulations for HELCO’s Post-April PSIP Plan (without batteries) in 2045.

Figure 41: Cumulative probability distribution of thermal generation over distinct weather simulations for HELCO’s Post-April PSIP Plan with Batteries in 2045.

4.6.2. The Optimization of Renewables and Batteries: The Ascend Plan
Unlike for the other islands, Ascend’s joint optimization of renewables and batteries contains no utility solar additions for Hawaii. The capacity factors on the Big Island are much higher for wind than solar, rendering additional wind without solar the optimal path forward for lowering Hawaii’s NPV portfolio costs.
Figure 42: Results of Ascend’s co-optimization of offshore wind, utility solar, and batteries for Maui.

Figure 42 presents that the optimal renewable mix for Hawaii contains 87% MW of additional onshore wind relative to the Hawaii Post-April PSIP Plan, combined with batteries. Figure 42 further presents that there is indeed a portfolio effect between batteries and the additional wind generation, confirming that batteries are essential for minimizing the NPV costs of Hawaii’s wind optimization plan.
Figure 43 presents the optimal levels of batteries for the Hawaii Ascend Plan, further driving home the economic benefits of the wind combined with batteries for Hawaii. The Hawaii Ascend Plan builds out battery capacity to 180 MWh, which is 35 MWh more battery capacity than in the Hawaii Post-April PSIP Plan with Batteries. Due to the absence of solar, the percent increase in battery installations from the Post-April PSIP Plan with Batteries to the Ascend Plan is lower for Hawaii relative to the two other islands. Nevertheless, with the additional battery capacity and wind generation, production costs begin to drop as early as 2022, revealing a pronounced portfolio effect between batteries and wind generation.

Figure 44 compares the difference in renewable capacities between the original Hawaii Post-April PSIP Plan and Ascend’s optimization of the plan (the Hawaii Ascend Plan). The Hawaii Post-April PSIP Plan has two 20-MW increases in onshore wind capacity, the first in 2020 and the second in 2030. Unlike the Oahu Ascend Plan, the Hawaii Ascend Plan does not increase the amount of renewable capacity at the same, fixed rate each year. The Hawaii Ascend Plan provides and 87% increase in onshore wind capacity over the entire study timeframe. Compared to the Post-April PSIP Plan, the Ascend Plan has installed an additional 125 MW of onshore wind capacity by 2045.
Figure 44: Comparison of renewable capacity additions between HELCO’s Post-April PSIP Plan and Ascend Plan.
When the Post-April PSIP Plan is optimized with batteries, Hawaii portfolio costs decrease by $94 M; when the original is optimized with batteries and renewables, yielding the Ascend Plan, Hawaii portfolio costs fall by 4%, or $149 M. The E3 Plan, however, increases portfolio costs by $181 M.

5. Flexibility Analysis

While most planning models assume perfect foresight in dispatch decision-making, such perfect decisions are impossible to make in the real world. On a minutely level, not only is load unpredictable, but with an energy portfolio containing a high level of renewables, generation can be unpredictable as well. Due to the unpredictable nature of both load and generation, batteries are an excellent option for flexible generation because of their very fast and precise charge/discharge capabilities in comparison to thermal generation units with its significant ramp-up times and high costs.

Ascend utilized the PowerSimm module, System Flexibility Software, to help the Companies determine future regulation requirements and the most cost effective ways of meeting those requirements. This section will first discuss Ascend’s System Flexibility Software, which calculates the Companies’ flexible generation requirements, such as regulation requirements, 15-minute ramps and 1-hour ramps. Then the section will consider PowerSimm’s determinations of the most cost-effective way to meet these flexible generation requirements.
5.1. System Flexibility Software

The objective of Ascend’s System Flexibility Software is to determine the amount of flexible generation capacity required when planning to integrate intermittent renewable energy sources into an energy system. Flexibility requirements are estimated in terms of (1) regulation requirements necessary to maintain CPS2 scores at 95 and 99.9, (2) ramping requirements at both 15-minute and 1-hour time steps, and 3) changes in ramping direction of net load. Due to the large proportion of solar generation, these requirements are estimated by day-time and night-time requirements. The software determines flexible generation requirements by estimating the variability of historical minutely data for load and renewable generation.

![Minutely Operations for Oahu 2020](image)

Figure 46: Oahu forecasted load, renewable generation and regulation for April 15th and 16th, 2020, with accompanying chart.

Figure 46 shows the central results provided by System Flexibility Analysis. The upper dark blue line indicates the load, which has relatively little variation, following the pattern of a muted sine wave. The light blue line denotes net load. Net load is calculated by subtracting solar (indicated by the yellow line), wind (indicated by the green line) and must-run thermal generation (not visually indicated in graphic) from system load. One of the aspects of intermittent renewables, especially solar, is significant, rapid fluctuations in generation, which causes parallel fluctuations in net-load, disrupting the originally quiescent sine wave pattern of system load. Thus, volatility in renewable generation by extension renders net load volatile. Regulation (indicated by the black line) is tasked with balancing out these fluctuations at a minutely level. These fluctuations are the difference between net-load following and minutely generation. Net load following, indicated by the red line, is measured as the linear hourly ramps based on
the hourly average of net load. The regulation requirement necessary to maintain CPS2 scores at 95 and 99.9 are signified by the red dotted line and blue dotted line respectively. CPS2 scores are a monthly cumulative measure of the area control error (ACE) that measure the divergence between energy supply and load. A large ACE would result in an increase or decrease in system frequency.

The intermittency of renewable generation largely determines the extent of regulation required. The regulation associated with load for 2020 is 167 MW, or approximately 18% of load. However, the higher renewable generation capacity in 2030 increases the amount of regulation to 313 MW, or 34% of load. As mentioned in the previous paragraph, regulation balances out the uneven generation in renewables. The off-peak (night-time) hours in Figure 46 reflects the joint variability in load and wind generation, which yield 18 MW of regulation requirements in 2020. On the other hand, the on-peak hours, when solar generation is active, result in a regulation requirement of 167 MW.

<table>
<thead>
<tr>
<th>Change in Solar Generation (MW)</th>
<th>Regulation Requirement (MW)</th>
<th>Percentage Increase of Regulation Requirement</th>
<th>Max 1-Hour Ramp (MW)</th>
<th>Percentage Increase of Max 1-Hour Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>167</td>
<td>--</td>
<td>688</td>
<td>--</td>
</tr>
<tr>
<td>+20</td>
<td>170</td>
<td>1.7%</td>
<td>691</td>
<td>0.4%</td>
</tr>
<tr>
<td>+40</td>
<td>174</td>
<td>4.2%</td>
<td>695</td>
<td>1.0%</td>
</tr>
<tr>
<td>+100</td>
<td>184</td>
<td>10.2%</td>
<td>706</td>
<td>2.6%</td>
</tr>
<tr>
<td>+200</td>
<td>202</td>
<td>21.0%</td>
<td>720</td>
<td>5.2%</td>
</tr>
<tr>
<td>+300</td>
<td>222</td>
<td>32.9%</td>
<td>741</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

*Table 5: Oahu, 2020 – flexible generation requirements with additions of solar capacity.*

<table>
<thead>
<tr>
<th>Change in Onshore Wind Generation (MW)</th>
<th>Regulation Requirement (MW)</th>
<th>Percentage Increase of Regulation Requirement</th>
<th>Max 1-Hour Ramp (MW)</th>
<th>Percentage Increase of Max 1-Hour Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>167</td>
<td>--</td>
<td>688</td>
<td>--</td>
</tr>
<tr>
<td>+20</td>
<td>168</td>
<td>0.6%</td>
<td>687</td>
<td>-0.1%</td>
</tr>
<tr>
<td>+40</td>
<td>169</td>
<td>1.1%</td>
<td>686</td>
<td>-0.3%</td>
</tr>
<tr>
<td>+100</td>
<td>171</td>
<td>2.3%</td>
<td>685</td>
<td>-0.4%</td>
</tr>
<tr>
<td>+200</td>
<td>176</td>
<td>5.3%</td>
<td>685</td>
<td>-0.4%</td>
</tr>
<tr>
<td>+300</td>
<td>181</td>
<td>8.4%</td>
<td>686</td>
<td>-0.3%</td>
</tr>
</tbody>
</table>

*Table 6: Oahu, 2020 – flexible generation requirements with additions of onshore wind capacity.*

A comparison of Table 5 and Table 6 illustrate the effect of increasing solar and onshore wind capacity on flexible generation requirements. As these results suggest, solar tends to have a more considerable effect on flexible generation requirements than wind. Solar has capacity factors of about 20% with the preponderance of generation in the six hours from 9 am to 3 PM. This concentration of solar generation leads to high ramps and the potential for curtailed energy. Moreover, the high spatial concentration of solar contributes to an even higher increase in regulation requirements per MW of added solar, relative to what is seen on the mainland. Complementing solar with wind mitigates the concentration effect with wind generating relatively uniformly over the day. As Table 6 shows, additional onshore wind capacity has a very limited effect on maximum 1-hour ramps, and even marginally lowers these ramps caused by solar,
due to its steadier rates of generation relative to solar. Wind has capacity factors in the state of Hawai‘i ranging from 40 to 70%.

Moreover, additional intermittent renewables increase the frequency of changes in the gradient for load following. Figure 47 shows how intermittent renewable generation can cause a sawtooth pattern in the red, net-load following line. In the morning hours of April 1st, 2032, the gradient of the net-load following changes 7 times.

![Minutely Operations for Oahu 2032](image)

*Figure 47: Oahu forecasted load, renewable generation and regulation for April 1st and 2nd, 2032.*

5.1.1. Oahu Results
The Daytime Regulation in Table 5 below is the regulation requirement necessary for maintaining a CPS2 score of 95. The Contingent Reserve is the power the energy system should be able to provide in the event of unusual load requirements. It is determined as 6% of peak load for the year. The Max 15-Minute Ramp and 1-Hour Ramp are the largest absolute values from Ramp Up and Ramp Down for their respective time steps, as found in the System Flexibility Software chart. On-Peak Total Flexible Generation is the total power capacity of the ancillary services in peaking conditions for that year. It is determined by summing Day-Time Regulation, Contingent Reserve and the Max 1-Hour Ramp for each year.
Table 7: Oahu renewable integration requirements for flexible generation. All results are unitized in MW.

As Table 5 indicates, Oahu’s flexible generation requirements grow considerably with the higher penetration of intermittent renewables over the years. The regulation requirements that Oahu will have to meet more than double in size from 2017 to 2025. Batteries and an updated flexible thermal fleet become crucial and cost-effective assets in meeting these requirements.

Figure 48 provides a visual, side-by-side comparison of renewable generation and flexible generation requirements for the same historic window (April 4th) in 2017 and 2025. The increase in solar generation appears to be the main driver of the increasing flexible generation requirements. In this time period, solar generation capacity (inclusive of DGPV) increases by 152%, from 629 MW to 1,587 MW. Flexible generation requirements in turn increase by 42%, from 761 MW to 1,081 MW.

Comparison of Minutely Operations for Oahu in 2017 and 2025
Figure 48: Side-by-Side comparison of renewable generation, load and regulation requirements on April 4th, 2017 and 2025. April 4th, 2017 is depicted on the left and April 4th, 2025 is depicted on the right.

5.1.2. Maui Results

The Maui Post-April PSIP Plan contains an installation of 80 MW of utility solar, and 90 MW of onshore wind in 2020, while in the other years there is no significant installation of renewables. Thus, flexible generation requirements for Maui grow at relatively conservative levels, with the exception of 2020, during which the flexible generation requirements increase by 61%.

<table>
<thead>
<tr>
<th>Year</th>
<th>Day-Time Regulation (95%)</th>
<th>Day-Time Regulation (99.9%) (A)</th>
<th>Contingent Reserve (B)</th>
<th>Max 15-Minute Ramp</th>
<th>Max 1-Hour Ramp (C)</th>
<th>On-Peak Total Flexible Generation (A+B+C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>38</td>
<td>76</td>
<td>12</td>
<td>88</td>
<td>111</td>
<td>199</td>
</tr>
<tr>
<td>2018</td>
<td>39</td>
<td>77</td>
<td>12</td>
<td>88</td>
<td>112</td>
<td>201</td>
</tr>
<tr>
<td>2019</td>
<td>39</td>
<td>79</td>
<td>13</td>
<td>90</td>
<td>113</td>
<td>205</td>
</tr>
<tr>
<td>2020</td>
<td>64</td>
<td>129</td>
<td>13</td>
<td>147</td>
<td>188</td>
<td>330</td>
</tr>
<tr>
<td>2021</td>
<td>64</td>
<td>129</td>
<td>13</td>
<td>147</td>
<td>188</td>
<td>330</td>
</tr>
<tr>
<td>2025</td>
<td>65</td>
<td>130</td>
<td>14</td>
<td>149</td>
<td>189</td>
<td>333</td>
</tr>
<tr>
<td>2030</td>
<td>66</td>
<td>132</td>
<td>13</td>
<td>150</td>
<td>191</td>
<td>336</td>
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<tr>
<td>2035</td>
<td>66</td>
<td>133</td>
<td>14</td>
<td>83</td>
<td>192</td>
<td>339</td>
</tr>
<tr>
<td>2040</td>
<td>71</td>
<td>142</td>
<td>15</td>
<td>165</td>
<td>215</td>
<td>372</td>
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<tr>
<td>2045</td>
<td>76</td>
<td>153</td>
<td>16</td>
<td>177</td>
<td>238</td>
<td>407</td>
</tr>
</tbody>
</table>

Table 8: Maui - Renewable integration requirements for flexible generation. Unlike for Oahu, On-Peak Total Flexible Generation is calculated using Day-Time Regulation Requirement necessary to maintain a CPS2 score of 99.9, as opposed to 95.

Figure 49 shows the effect of the additional renewable capacity in 2020 by providing a side-by-side comparison of forecasted renewable generation for April 13th, 2019 and 2020. With the additional onshore wind capacity, wind generation provides 50 to 60 MW of power throughout the day, as opposed to the negligible amount of power it provides during 2019. Solar generation levels also increase, peaking at around 200 MW in 2020 compared with 140 MW in 2019. The additional renewable generation causes the net-load to be negative for the day, indicating that there is excess dump energy which batteries can capture.
Figure 49: Side-by-side comparison of renewable generation, load and regulation requirements on April 13th, 2029 and 2030.

5.1.3. Hawaii Results
Since the Hawaii Post-April PSIP Plan only installs onshore wind, the percent increase of flexible generation requirements for Hawaii is the lowest of all the islands.

<table>
<thead>
<tr>
<th>Year</th>
<th>Day-Time Regulation (95%)</th>
<th>Day-Time Regulation (99.9%) (A)</th>
<th>Contingent Reserve (B)</th>
<th>Max 15-Minute Ramp</th>
<th>Max 1-Hour Ramp (C)</th>
<th>On-Peak Total Flexible Generation (A+B+C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>18</td>
<td>43</td>
<td>11</td>
<td>63</td>
<td>108</td>
<td>136</td>
</tr>
<tr>
<td>2018</td>
<td>19</td>
<td>44</td>
<td>12</td>
<td>63</td>
<td>109</td>
<td>139</td>
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<tr>
<td>2019</td>
<td>19</td>
<td>45</td>
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<td>141</td>
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<tr>
<td>2020</td>
<td>20</td>
<td>48</td>
<td>12</td>
<td>62</td>
<td>111</td>
<td>142</td>
</tr>
<tr>
<td>2021</td>
<td>21</td>
<td>49</td>
<td>12</td>
<td>63</td>
<td>112</td>
<td>144</td>
</tr>
<tr>
<td>2025</td>
<td>21</td>
<td>50</td>
<td>12</td>
<td>63</td>
<td>113</td>
<td>145</td>
</tr>
<tr>
<td>2030</td>
<td>22</td>
<td>52</td>
<td>12</td>
<td>60</td>
<td>110</td>
<td>142(^4)</td>
</tr>
<tr>
<td>2035</td>
<td>23</td>
<td>54</td>
<td>12</td>
<td>64</td>
<td>116</td>
<td>148</td>
</tr>
<tr>
<td>2040</td>
<td>24</td>
<td>56</td>
<td>13</td>
<td>68</td>
<td>124</td>
<td>158</td>
</tr>
<tr>
<td>2045</td>
<td>25</td>
<td>59</td>
<td>14</td>
<td>73</td>
<td>132</td>
<td>172</td>
</tr>
</tbody>
</table>

Table 9: Hawai‘i - renewable integration requirements for flexible generation. Unlike for Oahu, On-Peak Total Flexible Generation is calculated using Day-Time Regulation Requirement necessary to maintain a CPS2 score of 99.9, as opposed to 95.

\(^4\) The lower flexible generation requirements in 2030 relative to 2025 is a function of decreasing load.
In 2028, Hawaii plans to increase its on-shore wind capacity by 20 MW. Figure 50 offers a comparison of the difference in wind generation between 2029 and 2030.

**Comparison of Minutely Operations for Hawaii in 2028 and 2029**

![Comparison of Minutely Operations for Hawaii in 2028 and 2029](image)

*Figure 50: Side-by-side comparison of renewable generation, load and regulation requirements on April 4th, 2027 and 2028. April 4th, 2027 is depicted on the right and April 4th, 2028 is depicted on the left.*

Figure 50 indicates that the expansion in wind capacity causes a slight increase in wind generation. This wind expansion does not have a drastic effect on regulation requirements: The regulation requirements from 2029 to 2030 increase by 1 MW.

### 5.2. Flexible Generation and Batteries

PowerSimm compares thermal generation to batteries and calculates the savings that could be realized through the use of batteries. PowerSimm takes regulation requirements, as determined by System Flexibility Software, as input and determines the most cost-effective way to meet those requirements. PowerSimm calculates not only the savings from using batteries to meet regulation requirements, but it also calculates the savings that can be realized by using flexible batteries to smooth out the sawtooth changes in the net-load gradient induced by renewable generation contributions and daily ramps.

First, this section will define the three different types of batteries presented in this report. Then, this section will discuss the use of batteries to meet regulation requirements. Lastly, this section will discuss the use of flexible batteries.

#### 5.2.1. Three Types of Batteries

This report discusses three different types of batteries:

1) **Regulation batteries** are batteries that are used to meet regulation requirements, discharging and charging on a minutely scale to respond to minor fluctuations in load and generation. Ascend has assumed that regulation batteries have a seven-year lifetime due to their extremely frequent charging/discharging.

2) **Flexible batteries** are used to respond to daily cycles and ramps, discharging and charging on an hourly scale to smooth out changes in the net-load gradient induced by high levels of renewable
generation. Ascend assumed that flexible batteries have a twelve-year lifetime due to their less frequent charging/discharging.

3) **Load-shifting batteries**, which have already been discussed in the larger report, are used to absorb excess renewable generation during the day and discharge that energy at night. Thus, load-shifting batteries charge/discharge on a daily scale. Ascend assumed that load-shifting batteries have a fifteen-year lifetime due to their rather infrequent charging/discharging.

While the advantages of load-shifting batteries were discussed in Section 4, this section focuses on the advantages of batteries to furnish flexible regulation and smooth out rapid changes in load following cycles.

### 5.2.2. Regulation Batteries

The benefits derived from regulation batteries consists of two key elements. The first is the avoided fuel cost that comes from using batteries to provide regulation services. Below, Figure 51 shows thermal units have a declining heat rate as generation increases. Thus, thermal units operate more efficiently as they run closer to full load capacity. When thermal units serve regulation, they operate below their full load capacity, at a heat rate close to the midpoint. Using batteries to provide regulation enables thermal generators to avoid operating at these inefficient levels and save fuel costs. Additionally, batteries have the potential to eliminate costly start-ups from thermal generation. For example, the start-up costs for a combustion turbine of 100 MW is approximately $8,000 dollars. Using batteries to furnish regulation instead can avoid these start-up costs.

![Combined Cycle vs. Steam Unit Heat Rates](image)

*Figure 51: Typical heat-rate curve for combined-cycle and coal generators.*

The second element of battery benefits is capacity savings. When batteries furnish regulation, they effectively free up thermal generation that would otherwise be used to serve regulation. This freed up thermal generation can then be diverted to serve capacity, and, in turn, run at more efficient levels.
To compare the supply cost of thermal regulation to the cost of installing regulation batteries for Oahu, the cost-savings calculations consider the levelized cost of regulation batteries. This calculation multiplies the required battery capacity by the effective capital cost of battery installation. This calculation assumes a seven-year lifetime for regulation batteries, and it also assumes that, after seven years, the batteries are worth 50% of the cost of installation at that time. The levelized cost calculation spreads the capital costs of batteries over a seven-year period with an eight percent interest rate. These calculations ultimately show that the supply cost of thermal regulation is consistently much greater than the levelized capital costs for installing regulation batteries. These results are shown below in Table 10 and Figure 52.
<table>
<thead>
<tr>
<th>Year</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
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<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
</tr>
</thead>
</table>

**Regulation Requirements**

<table>
<thead>
<tr>
<th>Year</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
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<th>2028</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-peak Regulation Requirement (GWh/yr)</td>
<td>392</td>
<td>499</td>
<td>506</td>
<td>640</td>
<td>652</td>
<td>824</td>
<td>838</td>
<td>850</td>
<td>860</td>
<td>873</td>
<td>886</td>
<td>903</td>
<td>916</td>
</tr>
<tr>
<td>Off-peak Regulation Requirement (GWh/yr)</td>
<td>80</td>
<td>88</td>
<td>88</td>
<td>88</td>
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<td>88</td>
<td>88</td>
<td>88</td>
<td>88</td>
<td>88</td>
<td>166</td>
<td>166</td>
</tr>
</tbody>
</table>

**Regulation Battery Capacity Requirements (MWh)**

<table>
<thead>
<tr>
<th>Year</th>
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<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
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<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
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<th>2031</th>
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<tbody>
<tr>
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<td>32</td>
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<td>52</td>
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<td>56</td>
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<td>58</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Regulation Costs and Savings**

<table>
<thead>
<tr>
<th>Year</th>
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<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levelized Battery Costs - Regulation ($/yr)</td>
<td>($2)</td>
<td>($2)</td>
<td>($2)</td>
<td>($3)</td>
<td>($4)</td>
<td>($3)</td>
<td>($3)</td>
<td>($3)</td>
<td>($3)</td>
<td>($3)</td>
<td>($3)</td>
<td>($3)</td>
<td>($3)</td>
</tr>
<tr>
<td>Savings From Batteries for Regulation ($/yr)</td>
<td>$11</td>
<td>$15</td>
<td>$16</td>
<td>$21</td>
<td>$23</td>
<td>$29</td>
<td>$31</td>
<td>$34</td>
<td>$36</td>
<td>$38</td>
<td>$41</td>
<td>$47</td>
<td>$50</td>
</tr>
</tbody>
</table>

*Table 10: PowerSimm calculation results for regulation battery savings for Oahu.*
As the above figure shows, regulation batteries offer a prompt reduction in costs upon the first year of their introduction. Over the course of six years, with their capacity approximately doubling, savings from regulation batteries nearly triples.

5.2.3. Flexible Batteries
While regulation batteries provide high-frequency and short-duration charges and discharges to balance the difference between generation and load, flexible batteries serve longer-duration but less frequent cycles. Flexible batteries are usually of a duration of a couple hours and geared toward smoothing out the sawtooth pattern in hourly net load, as well as meeting daily ramps. Flexible batteries provide cost savings by preventing thermal units from running at inefficient heat rates. These savings are further aided through utilizing free dump energy to meet ramps and cycles, instead of producing that energy with thermal generation.

To compare the supply cost of thermal generation to flexible batteries for Oahu, the fuel cost and start-up cost savings of flexible batteries are measured against the capital costs of flexible batteries. The levelized cost of flexible batteries are measured over an assumed life of twelve years with an eight percent interest rate. PowerSimm’s calculations show that, starting in the year 2022, flexible batteries provide substantial savings over thermal generation. These results are presented below in Table 11 and Figure 53.
<table>
<thead>
<tr>
<th>Year</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible Generation Requirements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramp/Cycle Mgmt Energy Requirement (GWh/yr)</td>
<td>36</td>
<td>40</td>
<td>154</td>
<td>173</td>
<td>196</td>
<td>213</td>
<td>241</td>
<td>255</td>
<td>253</td>
<td>256</td>
</tr>
<tr>
<td>Dumped Energy (available for battery storage) (GWh/yr)</td>
<td>67</td>
<td>87</td>
<td>185</td>
<td>214</td>
<td>251</td>
<td>289</td>
<td>331</td>
<td>377</td>
<td>620</td>
<td>663</td>
</tr>
<tr>
<td>Battery Capacity Required for Ramp/Cycle Mgmt (MWh)</td>
<td>117</td>
<td>130</td>
<td>508</td>
<td>570</td>
<td>646</td>
<td>702</td>
<td>792</td>
<td>839</td>
<td>832</td>
<td>841</td>
</tr>
<tr>
<td>Flexible Generation Costs and Savings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Supply Costs to Provide Ramps/Cycle Mgmt ($M/yr)</td>
<td>($2)</td>
<td>($2)</td>
<td>($7)</td>
<td>($9)</td>
<td>($10)</td>
<td>($12)</td>
<td>($14)</td>
<td>($15)</td>
<td>($16)</td>
<td>($16)</td>
</tr>
<tr>
<td>Thermal Gen Costs to Produce Dumped Energy ($M/yr)</td>
<td>($7)</td>
<td>($8)</td>
<td>($34)</td>
<td>($39)</td>
<td>($47)</td>
<td>($53)</td>
<td>($62)</td>
<td>($69)</td>
<td>($71)</td>
<td>($75)</td>
</tr>
<tr>
<td>Total Thermal Costs (Dump Energy Generation + Ramp/Cycle Mgmt) ($M/yr)</td>
<td>($9)</td>
<td>($10)</td>
<td>($41)</td>
<td>($48)</td>
<td>($57)</td>
<td>($65)</td>
<td>($76)</td>
<td>($84)</td>
<td>($86)</td>
<td>($91)</td>
</tr>
<tr>
<td>Levelized Battery Costs - Ramp/Cycle Mgmt ($M/yr)</td>
<td>($5)</td>
<td>($6)</td>
<td>($22)</td>
<td>($25)</td>
<td>($28)</td>
<td>($30)</td>
<td>($34)</td>
<td>($34)</td>
<td>($34)</td>
<td>($34)</td>
</tr>
<tr>
<td>Savings From Batteries for Flexible Generation ($M/yr)</td>
<td>$4</td>
<td>$4</td>
<td>$19</td>
<td>$23</td>
<td>$29</td>
<td>$34</td>
<td>$42</td>
<td>$50</td>
<td>$52</td>
<td>$57</td>
</tr>
</tbody>
</table>

*Table 11: PowerSimm calculation results for flexible battery savings for Oahu.*
Figure 53: Yearly savings from using batteries for flexible generation instead of ULSD thermal generation.

Figure 15 indicates that, upon an introduction of flexible batteries into the energy system by 2022, flexible batteries provides an immediate reduction in costs, though not to the same extent as regulation batteries. By 9 years after their introduction, increased use of flexible batteries can save $57 million per year.

6. Addendum A: Incorporating Uncertainty in Resource Selection

Since the Companies have an obligation to minimize future costs, it is essential to analyze different energy supply options under many possible future conditions. While traditional modeling approaches utilize “normal” weather years and smooth fuel price trajectories, evaluating energy supply options under this single set of future conditions will almost certainly not reveal the lowest-cost energy supply portfolio over all future conditions. PowerSimm stochastically simulates future conditions, including market fuel prices and weather conditions, which drive renewable generation and load. Thus, PowerSimm provides a systematic approach for selecting the lowest-cost energy supply option over a broad range of future conditions. In addition, by simulating a range of future conditions, PowerSimm is able to quantify the risk associated with a particular energy supply option. This section will, first, elucidate the way in which PowerSimm simulations can be utilized to select the best energy supply option over all future conditions, and second, how PowerSimm quantifies the risk associated with a particular energy supply portfolio.
6.1. Stochastic Modeling and Optimal Resource Selection

The PowerSimm capacity expansion logic selects from an array of thermal and renewable assets to provide an evaluation of the optimal mix of these two types of assets. To perform this optimization, the PowerSimm modeling framework probabilistically envelopes future conditions to aid in optimal resource selection over all future states. Although Ascend could utilize deterministic runs with a single set of future conditions to assess the value of different supply portfolios, such an approach would ignore volatility and uncertainty in crucial variables, such as weather and fuel prices. For example, Figure 54 displays five PowerSimm-simulated Oil price trajectories through 2028. This figure demonstrates how Ascend’s PowerSimm software uses multiple simulations of driving variables to probabilistically envelope future conditions.

**Figure 54: Five PowerSimm simulations of oil prices through 2028.**

Thus, Ascend has found that deterministic runs can bias modeling results because of their limited path into the future. Instead, by simulating these variables, Ascend can assess the value of supply portfolios over a broad range of future conditions, and in turn, Ascend can determine which supply portfolios perform the best over all future conditions. Below, Figure 55 illustrates the difference in results between a deterministic run and a stochastic simulation that envelopes a range of future states.
In Figure 55, the deterministic result yields only one portfolio cost value. However, many stochastic simulations yield a distribution of portfolio cost values with a mean portfolio cost that differs from the deterministic result. The deterministic result is biased by user-determined weather conditions and fuel prices, whereas the stochastically-simulated mean reflects a wide range of future conditions. In this way, the PowerSimm framework can be used to develop unbiased results that take uncertainty into account.

To further illustrate this point using Figure 56, Ascend draws a sporting analogy for resource selection under uncertainty. Selecting the optimal energy portfolio over a deterministic run is equivalent to finding the best swimmer (Michael Phelps), the second deterministic run finds the best cyclist (Chris Froom), and the third deterministic run finds the best runner (Ryan Hall). However, in resource planning, we do not want the best athlete for any individual event, but the best athlete over all events – the best triathlete (Dave Scott). In the same way that the triathlete performs the best over multiple athletic events, the optimal energy portfolio performs the best over a wide range of future conditions. PowerSimm simulates this wide range of future conditions, allowing for the selection of the energy portfolio that performs best over all future conditions.

**Figure 55: Distribution of iteration-level results used to find stochastic result, versus deterministic result**
6.2. Calculating Risk Premium

Not only does PowerSimm aid in the selection of the optimal energy portfolio over a wide range of future conditions, but PowerSimm also identifies the risk associated with each energy portfolio option, quantifying this as the “risk premium.” The risk premium is defined as the probability-weighted average of costs above the median. This concept is illustrated below in Figure 57.
Since different energy portfolios have different simulated cost distributions, the risk premium will be larger for wider cost distributions, or riskier portfolios, and smaller for narrower cost distributions, or less risky portfolios. After calculating the risk premium, Ascend then adds the risk premium variable to the expected value in order to put all energy portfolio options on the same playing field.

6.3. Simulation Validation Tool

An energy system has to be prepared to not just confront normal weather conditions, but abnormal ones as well. Thus, PowerSimm accounts for a wide variability in possible future weather conditions and its consequent effects on load and generation. The following figures from the Simulation Validation Tool provide insight into the variability covered by PowerSimm.

The validation tool enables the user to scroll through time to view the variation in generation between four distinct weather simulations, as well as the average generation of total weather simulations run by PowerSimm.
Figure 58: Solar generation over 4 different weather scenario from January 3rd to th 7th, 2018.

Figure 58 presents solar generation over a five-day period. The Solar 4 simulation, indicated by the dark blue line, represents a scenario where solar generation is particularly low. During this period, the mean generation of the 20 distinct simulations of solar generation, represented by the light blue line, can be up to 3 times larger than the generation of the Solar 4 simulation.

Figure 59 provides an example of the variation in solar generation at a later time, in 2045. The dark blue line shows an abnormal weather scenario, over a two-day period, when solar generation is two to three times lower than for the average of the total scenarios.

Figure 59: Solar generation over different weather scenarios from December 7th to December 8th, 2045.

Figure 60 presents wind generation for a day in 2029, illustrating that the difference in generation between the 4 distinct weather simulations can vary by up to 500%.
Figure 60: Wind generation over 4 different weather scenarios for January 22\textsuperscript{nd}, 2029.

With the introduction of offshore wind in 2030, some of the variability in wind generation is mitigated, as offshore wind provides a more reliable source of generation than onshore wind. Figure 61 displays this lower variation.
Thus, as these figures show, PowerSimm incorporates a substantial amount of variability within its inputs. This variability enables PowerSimm to provide results that take into account normal weather scenarios, as well as extreme weather scenarios.

7. Addendum B: Model Inputs

With the PowerSimm modeling analysis, Ascend was able to further refine and optimize Oahu’s original plans. As part of this process, Ascend utilized new data and added new features to Oahu’s themes. Ascend has updated numerous forecasts and used these new forecasts as inputs to the PowerSimm model. This section will discuss updates to fuel forecasts, renewable forecasts, and customer load forecasts.

7.1. Fuel Forecasts

The United States Energy Information Administration (EIA) released a new fuel price forecast which has been included in Ascend’s analysis. This forecast included significantly higher oil prices but unchanged LNG prices from the forecast which was used to develop the original themes. Figure 62 shows the forecasted fuel prices used in Ascend’s modeling analysis.
As shown in Figure 62, LNG is the lowest-priced fuel, especially in the later decades of Ascend’s analysis. LSFO and ULSD are priced much higher than LNG, and biodiesel is the most expensive fuel of all.

7.2. Renewable Forecasts
In addition to updated fuel forecasts, Hawaiian Electric Companies also provided Ascend with new unitized offshore wind data and new unitized photovoltaic data which were used to create an updated offshore wind forecast and an updated photovoltaic forecast. The new offshore wind data resulted in a forecast with higher offshore wind capacity than previous calculations. Whisker plots for Oahu’s solar and wind generation are both shown below.
Figure 63: Oahu Theme 1 solar generation in 2045. Boxes span from 1st to 3rd quartile, with median in the middle. Whiskers cover the minimum and maximum simulated values.
Figure 64: Oahu Theme 1 wind generation in 2045. Boxes span from 1st to 3rd quartile, with median in the middle. Whiskers cover the minimum and maximum simulated values. Update

7.3. Customer Load Forecast
With the creation of an updated hourly customer load profile based on the Black & Veatch DR5 forecast, Ascend included this new load profile in its PowerSimm model. The monthly customer load forecast for Oahu in 2045 is shown below in Figure 65.
Figure 65: Oahu Theme 1 Black & Veatch DR5 customer load profile in 2045. Boxes span from 1\textsuperscript{st} to 3\textsuperscript{rd} quartile, with median in the middle. Whiskers cover the minimum and maximum simulated values.

8. Addendum C: Model Validation

To confirm that Ascend’s PowerSimm model is valid, Ascend compared simulated weather, load, and renewable generation data to historical data to ensure that they match. In addition, Ascend also compared generation capacity factors to Oahu’s values and simulated prices to forward data. The validation checks are shown in Table 12.

<table>
<thead>
<tr>
<th>Validation</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>• Benchmark 5\textsuperscript{th}, mean, 95\textsuperscript{th} of historical temperatures</td>
</tr>
<tr>
<td>Load</td>
<td>• Hourly load: 5\textsuperscript{th}, mean, 95\textsuperscript{th}</td>
</tr>
<tr>
<td></td>
<td>• Monthly load: 5\textsuperscript{th}, mean, 95\textsuperscript{th}</td>
</tr>
<tr>
<td>Renewables</td>
<td>• Hourly generation: 5\textsuperscript{th}, mean, 95\textsuperscript{th}</td>
</tr>
<tr>
<td>Generation Capacity Factors</td>
<td>• Match existing dispatch</td>
</tr>
<tr>
<td>Forward Curves</td>
<td>• Match 5\textsuperscript{th}, mean, 95\textsuperscript{th} of option ranges and expectation</td>
</tr>
</tbody>
</table>
Ascend conducted this validation process for Oahu, Maui, and Hawaii, which will be discussed in this subsection in turn. But first the Ascend’s Validation Tool will be reviewed.

### 8.1.1. Oahu Validation

Validation plots for Oahu weather, load, renewable generation, generation capacity factors, and forward curves are shown below. The following plots illustrates the agreement between

**Monthly Weather Validation**

*Figure 66: Shows that the historical weather data matches simulated weather data on the monthly level*
Weather and Load Correlation Validation

Figure 67: Shows that simulated weather and load data maintains the same relationship as historical weather and load data.
Figure 68: Shows that historical load data matches simulated load data on the monthly level.
Figure 69: Shows that historical load data matches simulated load data on the hourly level

Figure 70: Shows that historical solar generation matches simulated solar generation on the hourly level
### Generation Capacity Factor Validation

<table>
<thead>
<tr>
<th>Generation Station</th>
<th>Ascend Capacity Factors</th>
<th>OAHU Capacity Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>AES</td>
<td>0.91</td>
<td>0.93</td>
</tr>
<tr>
<td>CHEV</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>CIP</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>DSG</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>HIE</td>
<td>1.00</td>
<td>0.97</td>
</tr>
<tr>
<td>HP</td>
<td>0.53</td>
<td>0.43</td>
</tr>
<tr>
<td>Kahe</td>
<td>0.54</td>
<td>0.46</td>
</tr>
<tr>
<td>Kala CC</td>
<td>0.77</td>
<td>0.80</td>
</tr>
<tr>
<td>Waiau</td>
<td>0.13</td>
<td>0.17</td>
</tr>
</tbody>
</table>

*Table 13: Shows that the Ascend generation capacity factors match the Oahu generation capacity factors*
Figure 71: Shows simulated LNG, LSFO, and ULSD prices

8.1.2. Maui Validation
Validation plots for Maui weather and load are shown below.

Weather Validation
Figure 72: Shows that the historical weather data matches simulated weather data
Weather and Load Correlation Validation

Figure 73: Shows that simulated weather and load data maintains the same relationship as historical weather and load data
Monthly Load Validation

Figure 74: Shows that historical load data matches simulated load data on the monthly level

Hourly Load Validation
Figure 75: Shows that historical load data matches simulated load data on the hourly level

8.1.3. Hawaii Validation
Validation plots for Hawaii weather and load are shown below.

Weather Validation
Figure 76: Shows that the historical weather data matches simulated weather data
Weather and Load Correlation Validation

Figure 77: Shows that simulated weather and load data maintains the same relationship as historical weather and load data
Figure 78: Shows that historical load data matches simulated load data on the monthly level
9. Addendum D: Data for System Flexibility Software

Minutely data for System Flexibility Software was collected or proxied for each island for Load, Utility Solar, Customer Solar, On-Shore Wind, and Off-Shore Wind. Each island has 3 themes, with separate forecasts and assumptions corresponding to each.

**Oahu**

**Load**
Minutely data for O’ahu net load was shared from January 2014 through October 2015. This load data has a small amount of DGPV netted out of it.

**Utility PV**
Minutely Data for KREP and KS2 were summed from January 2014 through October 2015.

**Customer PV**
Unitized minutely profile for DGPV for 2014, provided by HECO.

**On-Shore Wind**
Minutely data for Kahuku and Kawailoa were summed from January 2014 to October 2015. Starting in 2035, Kahuku and Kawailoa were summed with themselves lagged 28 days (one lunar cycle) to represent increased spatial diversity.

**Off-Shore Wind**
Two-Second data for HRD was aggregated to minutely in April, August, and December 2014 and used as a proxy for off-shore wind due to similar capacity factors and correlation to On-Shore wind.

*Figure 79: Shows that historical load data matches simulated load data on the hourly level*
The overlapping time intervals for the above historical data was used for this analysis. Overlapping data existed for 3 months in April, August, and December 2014. Annual forecasts for each theme (1-3) contain separate Utility Solar, Customer Solar, On-Shore Wind, and Off-shore Wind Capacity assumptions, and Must-Run Thermal Generation Constraints. Load forecasts are constant between themes.

**Hawaii**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>HELCO shared a 2 second system load profile that was aggregated to minutely in April, August, and December 2014.</td>
</tr>
<tr>
<td>Utility PV</td>
<td>HELCO shared a 2 second PV profile that was aggregated to minutely in April, August, and December 2014.</td>
</tr>
<tr>
<td>Customer PV</td>
<td>HELCO shared a 2 second PV profile that was aggregated to minutely in April, August, and December 2014.</td>
</tr>
<tr>
<td>On-Shore Wind</td>
<td>Two-Second data for HRD and Tawhiri were aggregated to minutely in April, August, and December 2014.</td>
</tr>
</tbody>
</table>

The overlapping time intervals for the above historical data was used for this analysis. Overlapping data existed for 3 months in April, August, and December 2014. Annual forecasts for each theme (1-3) contain separate Utility Solar, Customer Solar, On-Shore Wind, and Off-shore Wind Capacity assumptions. Load forecasts are constant between themes.

**Maui**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>HELCO System Load was used as a proxy for MECO System Load in April, August, and December 2014.</td>
</tr>
<tr>
<td>Utility PV</td>
<td>HECO PV data was used as a proxy for MECO Solar</td>
</tr>
<tr>
<td>Customer PV</td>
<td>HECO PV data was used as a proxy for MECO Solar</td>
</tr>
<tr>
<td>On-Shore Wind</td>
<td>HECO Wind Data was used as a proxy for MECO wind</td>
</tr>
</tbody>
</table>

The overlapping time intervals for the above historical data was used for this analysis. Overlapping data existed for 3 months in April, August, and December 2014. Annual forecasts for each theme (1-3) contain separate Utility Solar, Customer Solar, On-Shore Wind, and Off-shore Wind Capacity assumptions. Load forecasts are constant between themes.