Project Imua

AN ECONOMIC ANALYSIS OF THE IMPACTS OF AMBRI STORAGE AND VARYING LEVELS OF RENEWABLES IN HAWAII FOR UTILITIES AND SELECT CUSTOMERS

ANALYSIS GROUP
AMBRI

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About Project Imua

*Project Imua* is a two-phased project funded by the Energy Excelerator to evaluate the economic and operational impacts of a new battery solution in Hawaii. The new energy storage solution – Ambri’s Liquid Metal Battery – has the potential to reduce energy costs, increase electric reliability, and enable further increases of renewable resources across the Hawaiian Islands.

The first phase of *Project Imua* is this report – a study focused on evaluating the potential economic impacts of deploying Ambri’s energy storage systems in Hawaii across different locations, customer segments, and applications – including utility systems, renewable power installations, and end-user locations. This economic analysis provides a useful framework to inform stakeholders of a variety of options and implications. Detailed site specific engineering studies will be required to fully determine all of the specific costs and benefits of specific projects. The second phase of *Project Imua* is the deployment of two prototype Ambri systems in Hawaii.

The Energy Excelerator (EEx) is a startup program dedicated to helping solve the world’s energy challenges, starting in Hawaii. The program is funded by the U.S. Department of Defense’s Office of Naval Research, U.S. Department of Energy, State of Hawaii, and corporate partners Hawaiian Electric Industries, Blackstone, DENSO, and Mathworks. The EEx supports the development and commercialization of advanced energy technologies in Hawaii by funding innovative companies and the development of strategic relationships.

The data and operating experience created by *Project Imua* will inform Hawaii’s electric industry participants and policymakers of the capabilities of Ambri’s storage systems and resource deployment options, and will help identify high-value locations for future systems in Hawaii and the Asia Pacific, at large. Project partners will be able to use the analysis and data to understand the value proposition of Ambri batteries, and determine beneficial future deployments of wind, solar and storage in Hawaii and other locations.

The Demonstration Project has a number of different partners, including:

- Ambri
- Hawaiian Electric Company
- Kauai Island Utility Cooperative
- SunEdison (formerly First Wind)
- Joint Base Pearl Harbor-Hickam
Acknowledgments

Analysis Group and Ambri wish to thank the Demonstration Project partners for their support of the analysis presented in this report. Their assistance in concept development, data gathering and processing, model construct and review, and evaluation of results greatly assisted in the completion of this valuation study. The report includes battery optimization modeling conducted by Analysis Group, and various storage economic valuation analyses completed by Ambri. The results, however, do not necessarily reflect the views of the Energy Excelerator or the other Demonstration Project Partners.

About Analysis Group

Analysis Group provides economic, financial, and business strategy consulting to leading law firms, corporations, and government agencies. The firm has more than 600 professionals, with offices in Boston, Chicago, Dallas, Denver, Los Angeles, Menlo Park, New York, San Francisco, Washington, D.C., Montreal, and Beijing.

Analysis Group’s energy and environment practice area is distinguished by expertise in economics, finance, market analysis, regulatory issues, and public policy, as well as significant experience in environmental economics and energy infrastructure development. The practice has worked for a wide variety of clients including energy producers, suppliers and consumers; utilities; regulatory commissions and other public agencies; tribal governments; power system operators; foundations; financial institutions; and start-up companies, among others.

About Ambri

Founded in 2010, Ambri Inc. (formerly known as Liquid Metal Battery Corporation) is based in Cambridge, Massachusetts, with systems testing and manufacturing operations located in Marlborough, Massachusetts. Ambri’s technology is the Liquid Metal Battery (LMB), an approach to energy storage that differs from any product commercially available or in development today. The LMB was invented in the lab of Dr. Donald Sadoway at Massachusetts Institute of Technology and has been designed from the beginning to be low cost, long lifespan, operationally flexible and safe. The research at MIT was supported by the Department of Energy’s ARPA-e program, the French energy company, Total, the Deshpande Center, and the Chesonis Family Foundation. Ambri has top-tier investors including Khosla Ventures, Total, Bill Gates, KLP Enterprises and Building Insurance Bern (GVB).
TABLE OF CONTENTS

Executive Summary 1
Background: Electricity in Hawaii 3
Case Studies 9
  1) Hawaiian Electric Company: Reducing rates while enabling increasing solar generation 9
  2) Maui: mitigating curtailment of wind generation 16
  3) Joint Base Pearl Harbor-Hickam: providing energy security and resiliency 20
  4) Reducing electricity costs for hotel and resort customers in Hawaii 26
APPENDIX 1. Additional select information on specific case studies 32
APPENDIX 2. Specifications of Ambri’s Liquid Metal Battery 40
APPENDIX 3. Analysis Group’s Renewable/Storage Optimization Model 43
APPENDIX 4. HECO financial model details and discussion 46
Figure 1. Left: Hawaiian retail rates are more than triple the U.S. average; Right: Today’s Hawaiian retail rates are dependent on crude oil prices ................................................................. 3
Figure 2. KIUC frequency during solar vs. non-solar hours ........................................................................... 6
Figure 3. Distributed PV on distribution circuits on Oahu (August 2015). Left: as a percentage of daytime minimum load; Right: as a percentage of peak load. ................................................................. 6
Figure 4. Oahu System Load Profile shift, 2006-2014 ..................................................................................... 7
Figure 5. Hawaii’s “Nessie Curve”: average 46kV transformer loading, and example of severe system backfeed condition on 8/8/13 ................................................................. 7
Figure 6. Typical September net load profiles ................................................................................................. 11
Figure 7. Example HECO feeder profile with 3 MW of solar. Top: without storage, net load is highly variable and peaks at 1.97 MW. Bottom: 7 MWh of Ambri storage serves to flatten net load, avoid backfeed of excess solar generation, and reduce overall peak net load by 50% ........................................................................................................... 13
Figure 8. HECO “Future Energy Scenario” (base case results) .................................................................... 14
Figure 9. “Future Energy Scenario” sensitivities, shown alongside the sensitivity of today’s generation mix to different oil price forecasts ................................................................. 15
Figure 10. Left: HECO total wind energy accepted and rejected by time of day. During some hours, curtailment is as high as 50%. Right: Example of wind variability and the effect on MECO frequency. .............................................. 18
Figure 11. Net Benefits to SunEdison of adding incremental amounts of storage capacity, from 5 MWh to 25 MWh ......................................................................................................................... 19
Figure 12. Cumulative benefits of various levels of energy storage ................................................................ 19
Figure 13. JBPHH Load Analysis using 2012 load data demonstrates that a 50 MWh battery could reduce monthly peak by an annual average of 6.5 MW ........................................................................ 22
Figure 14. Building 166: Hours with positive net load with various levels of Ambri storage and solar generation ............................................................................................................................. 24
Figure 15. Hickam: Hours with positive net load with various levels of Ambri storage and solar generation ... 25
Figure 16. Twelve months of hotel electricity bills, by charge type ................................................................. 27
Figure 17. Twelve months of hotel demand charges ...................................................................................... 27
Figure 18. Total renewable energy consumption at various levels of solar and storage capacities .................. 29
Figure 19. Project NPV at various levels of solar and storage capacities ......................................................... 29
Figure 20. 1.5 MW of solar and 4 MWh of storage; 100 percent debt financed (base case) .............................. 30
Figure 21. Base case annual expense reductions demonstrate diminishing returns of solar-only capacity build-out, as compared to ongoing and greater benefits of solar-plus-storage resource additions. Storage sized optimally based on level of solar in each scenario ........................................................................................................ 32
Figure 22. Step 1 towards HECO future energy scenario ............................................................................ 32
Figure 23. Step 2 towards HECO future energy scenario ............................................................................ 32
Figure 24. Step 3 towards HECO future energy scenario ............................................................................ 32
Figure 25. HECO future energy scenario (high oil case: 199/barrel) ............................................................ 34
Figure 26. HECO future energy scenario (low oil case: $73/barrel) .............................................................. 34
Figure 27. HECO future energy scenario (high storage case: $1000/kWh) ................................................... 35
Figure 28: Box plot of KWPII curtailment by hour of day across April 2014. Majority of curtailment overnight and during peak solar generation hours.

Figure 29: Detailed KWPII availability, output, and curtailment levels over three day period in April 2014.

Figure 30. Net Present Values using 10% Investment Tax Credit (ITC).

Figure 31. Different effective retail rates by solar-plus-storage scenario.

Figure 32. Seasonal variability of hotel load.

Figure 33. Weekday variability of hotel load.

Figure 34. Operating mechanisms of the Ambri battery cell.

Figure 35. Ambri’s battery systems can provide simultaneous capabilities to the electric grid.

Figure 36. Commercial 1 MWh Ambri System Architecture.

Figure 37. Inputs, optimization criteria, and outputs of Analysis Group’s Renewable & Storage Optimization (RSO) model.

Figure 38. HECO total annual expenses methodology.
INDEX OF TABLES

Table 1. Simulation results of solar-plus-storage scenarios for a group of four HECO distribution feeders serving a 20 MW peak load.................................................................10
Table 2. Description of four HECO feeders analyzed........................................................................11
Table 3. Financial inputs and assumptions for Base Case model .........................................................37
Table 4. Additional HECO case study solar and storage cost inputs and sensitivities reviewed..............49
EXECUTIVE SUMMARY

This report examines the economic and operational impacts that Ambri’s energy storage systems may have in four (4) specific use cases in Hawaii. While Hawaii faces unique challenges, the conclusions contained in this report are applicable to other jurisdictions, many of which are looking to Hawaii as a “postcard from the future” with respect to renewable energy integration.

The four case studies were selected to enumerate the various value streams that Ambri’s storage systems can provide to different constituents across the electricity value chain. Modeling utilized hourly or more frequent load, solar, wind generation data from Hawaii to determine specific charging, discharging profiles as well as conventional and renewable generation. Benefits evaluated include reductions in retail electricity costs, significant reductions in fossil-fuel use and expenditures for non-domestic fuel supplies used within Hawaii’s existing power systems; avoided and deferred capital investment in power generation and supply infrastructure; and reduced emissions of carbon dioxide (CO₂) and other pollutants.

Not all benefits and costs were quantified and modeled in this analysis. Detailed site specific engineering is required to determine specific costs and benefits of any individual proposed project. Examples of costs not modeled include potential changes required by the utility to plan, manage and control the revised grid, or other site specific costs for distribution system upgrades or expenditures. Examples of benefits not modeled or quantified include reductions in financial risk associated with exposure to oil price volatility; increases in power supply quality and security; the ability to support transmission and distribution system operations and reliability; facilitation of the integration of increasing levels of renewable resources, both distributed and grid-scale; and maximizing the economic and reliability value of variable renewable resources.

1) The first case study evaluates the addition of Ambri storage at four different Hawaiian Electric Company (HECO) distribution feeders as the level of solar generation located on those feeders increases. The analysis shows that energy storage can serve to reduce and flatten the generation required from the conventional grid, allowing for substantially higher levels of solar penetration than would otherwise be possible, while reducing strain on the distribution network equipment. Additionally, solar generation (modeled as costing $0.10 per kWh) paired with Ambri’s energy storage could provide over 80 percent of the annual electricity needs, while delivering electricity to ratepayers at a projected average retail rate of $0.24¹, a 23 percent cost reduction compared to current prices. This transformation provides retail price stability equivalent to securing $80/barrel oil for the next 20 years and beyond, while mitigating global supply and pricing risks. At the same time, the increased solar enabled by this energy storage could displace up to 58,000 MWh of diesel fired generation at these four feeders, reducing carbon emissions by approximately 43,000 metric tons of carbon dioxide each year.

2) The second case study evaluates the integration of Ambri’s storage with SunEdison’s Kaheawa Wind Power II (KWPII) Farm on Maui to mitigate the curtailment of wind generation from this plant. The analysis demonstrates that SunEdison could increase revenues at KWPII by 10% annually with the

¹ Uses 2014 HECO expenses as a baseline. Full details on cost modelling described in Appendix 4.
addition of energy storage at a net present value of $1.6 million for a 10 MWh Ambri system, with ratepayers on Maui also receiving the additional societal benefits of reduced diesel power consumption.

3) The third case study evaluates the integration of renewables with Ambri storage on or at Joint Base Pearl Harbor-Hickam (JBPHH) to minimize JBPHH power costs as well as insulate mission critical energy needs from civilian grid disruptions. The analysis demonstrates that with 50 MW of renewable power and 50 MWh of Ambri energy storage, the Hickam portion of JBPHH would be electrically largely self-reliant, providing all its electricity needs for 60 percent of hours per year. Further, 150 MW of renewable power and 200 MWh of Ambri energy storage would provide all of the Hickam base’s electricity needs for approximately 98 percent of hours. Even without additional renewable energy generation, a 50 MWh battery would provide an average peak reduction of 6.5 MW per month. This peak shaving would lower total demand charges by approximately $1.6 million per year.

4) The fourth and final case study evaluates the integration of renewable resources and Ambri storage at a commercial hotel in Honolulu. Solar plus storage system will yield electricity cost savings, with potential to operate year-round without connection to the surrounding electricity grid if augmented with limited use back up generation. With 2 MW of renewables and 6 MWh of Ambri storage, the hotel will operate independent of grid power 95 percent of the time, at an effective rate of $0.25/kWh, 17 percent lower than the current electricity rate paid by the hotel. Finally, with project returns in the 20-25 percent range for a non-leveraged finance structure, these economics present an attractive business model for project developers to offer the hotel a combined solar-plus-battery asset under a power purchase agreement (PPA).

Among U.S. states, Hawaii is a leader in deploying energy storage to address the challenges associated with both the rapid growth of renewables and the significant share renewables provide as a portion of peak load on the islands. The state has 18 energy storage projects operational as of this report’s publication date, across a range of technology types, including lithium ion, lead acid, flow, sodium nickel chloride batteries.²

Ambri’s approach to energy storage is novel: the Liquid Metal Battery is the only battery where all three active components – two metal electrodes separated by a molten salt electrolyte – are liquid when the battery operates.³ This technology offers a number of important advantages from the perspectives of flexibility, economics, power system operation and reliability, and safety. The battery cell is simple to manufacture, uses earth-abundant materials, and the all-liquid design avoids the main failure mechanisms experienced by solid components in other battery technologies. As a result, the Ambri battery can maintain efficiency and operability for a very long time, and is modeled as having a twenty-year lifespan. The purpose of the current economic feasibility analysis is to assess and quantify, when possible, the full range of these benefits.

³ Additional details on Ambri’s battery operating mechanisms are described in detail in Appendix 2.
BACKGROUND: ELECTRICITY IN HAWAII

Among all U.S. states, Hawaii’s electricity landscape is unique. The State faces a very high cost of electric service, heavy dependence on imported fuels, and substantial potential for local renewable generation including wind and solar to meet most or all electricity needs.

1) Hawaii has **very high electricity rates**, driven almost entirely on the price of oil. In 2013, the price of oil averaged $109/barrel⁴ and resulted in average electricity rates of $0.33/kWh in Hawaii, almost triple the national average in the United States. This is common in island states and nations – for example the average retail rate in the Caribbean in 2012 was $0.33/kWh with some nations as high as $0.43/kWh.⁵

![Figure 1. Left: Hawaiian retail rates are more than triple the U.S. average⁶; Right: Today’s Hawaiian retail rates are dependent on crude oil prices](image)

2) Hawaii **generated over 80 percent of its electricity from fossil sources in 2013;⁷** in contrast, the U.S. as a whole meets only one (1) percent of its electricity needs from diesel-generated power.⁸ Overall, Hawaii’s energy supply is more than 20 percent more carbon intensive (i.e., kilogram of energy-related CO₂ per MMBtu) than the U.S. as a whole.⁹

3) Hawaii has **abundant indigenous renewable resources** and is a **leader in renewable energy** today. In 2014 the State met more than 21 percent of its electricity needs with renewables.¹⁰ By comparison, in 2014, the U.S. as a whole met 13 percent¹¹ of its electricity needs from renewable energy. Recently, Hawaii passed legislation setting a state renewable portfolio standard (RPS) of **100 percent**

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⁴ See, historical commodity prices for Crude Oil prices from IndexMundi, available at http://www.indexmundi.com/commodities/?commodity=crude-oil-brent&months=120.
⁵ Inter-American Development Bank, Caribbean DEV'Trends, “The Caribbean has some of the world’s highest energy costs – now is the time to transform the region’s energy market,” available at http://blogs.iadb.org/caribbean-dev-trends/2013/11/14/the-caribbean-has-some-of-the-worlds-highest-energy-costs-now-is-the-time-to-transform-the-regions-energy-market/ (downloaded August 14, 2015).
⁶ Energy Information Administration, Average retail price of Electricity to ultimate customers, by state, available at http://www.eia.gov/electricity/data/browser/#/topic/7
renewable energy by 2045. A 2009 study identified over 4,000 MW of potential renewable energy capacity in the state, including over 2,000 MW of potential rooftop solar and over 2,000 MW of utility-scale projects including solar, wind and biomass. 12 In order to capture the maximum potential of its local renewable resources, Hawaii will need to address challenges that arise from integrating into the electric system large amounts of distributed solar and increasing amounts of utility-scale wind and solar projects, given the intermittent nature of these resources. In fact, Hawaii is already facing challenges today at the distribution level, as the penetration of distributed solar increases.

4) Hawaii is comprised of seven standalone electric grids – currently it is not possible to move electricity between islands.13 This presents unique infrastructure challenges because much of the balancing that can happen across a large electricity system cannot happen as easily in Hawaii. Hawaii’s circumstances today are similar to those faced by other island nations or remote grids – for example, utilities in the Caribbean and remote villages in Alaska.

In response to these challenges, state policy makers have set clear directives for a new path in the demand and supply of electricity, paving the way for Hawaii to leap ahead of other states in creating a 21st century generation system and modern transmission and distribution grids. The Hawaiian Electric utilities – through their Power Supply Improvement Plan (PSIP) Filings – have already put substantial effort towards envisioning a new energy future in Hawaii.14 Specifically, the utilities are aggressively pursuing renewables development (and the system upgrades to support it), alternative electricity supply plans, demand side management, and alternative structures for industry organization and electricity pricing, all to foster the move towards a long-term, sustainable electric future.

However, increasing levels of variable renewable energy pose several operational challenges for Hawaiian utilities and energy consumers. These can include:

- The large supply of renewable generation on distribution feeders negatively impacts distribution equipment loading, system frequency and voltage, making it more difficult to operate and protect the distribution system.15 Hawaii has experienced some of the largest adoption rates of distributed photovoltaic (PV) systems in the nation. In fact, as of January 2015, Hawaii had nearly 52,000 solar owners.16 To help manage the impact on any one distribution feeder, HECO has implemented a distributed generation cap of 120 percent of daytime minimum load, above

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which (and up to 250 percent of daytime minimum load), special permits and inverter technologies are required for interconnection consideration.¹⁷

- **Hawaii’s utilities have to curtail wind generation.** Wind curtailment levels have been considerable on Maui (MECO) and on the island of Hawaii (HELCO), and curtailment occurs primarily during low load hours. This issue has been exacerbated by the rapid growth in PV installations.¹⁸ In fact, in some cases, increasing levels of solar generation have forced Hawaii’s utilities to curtail more wind generation, rather than displacing diesel generation.¹⁹ For example, Maui Electric (MECO) curtailed 46.7 GWh of wind energy in 2013, or about 17 percent of all wind energy generated.²⁰

- **It is increasingly challenging to manage moment-to-moment fluctuations in frequency and voltage as a result of ramp-rate excursions from wind and solar.** One of the biggest challenges associated with wind and solar power is that they are, by nature, inherently intermittent. When clouds roll in or the wind subsides, utilities need to be able to accommodate sudden drops in output; similarly when the sun comes back out or the wind picks up, utilities need to be able to accommodate the sudden increase in supply on their system. Hawaii’s fleet of diesel generation plants is struggling to meet these challenges. For example, a recent MIT Technology Review article explains what this means for Kauai:

> “Kauai’s difficulty is most acute when clouds drift over a solar plant. That can slash a plant’s power output by 70 to 80 percent in less than a minute. If the plant is providing a substantial share of the grid’s power, that rapid power loss can cause the frequency of the grid’s alternating current to drop well below 60 hertz, damaging customer equipment or even causing a blackout.”²¹

To illustrate how solar generation can cause frequency regulation issues, consider Figure 2, which shows the Kauai Island Utility Cooperative’s (KIUC) system frequency levels for a week during August 2014.²² The yellow shaded area represents the hours between 6am – 6pm when the sun is shining, and identifies a clear correlation between solar generation and system frequency. A frequency change of 0.1Hz would be a major frequency excursion for most interconnected grids in North America,²³ and yet island grids such as KIUC’s and HECO’s are regularly dealing with excursions of 0.2 – 0.3 Hz.

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¹⁹ Conversation with Hawaiian Electric Company representatives.
²² Frequency data provided by KIUC as a partner to this study.
Figure 2. KIUC frequency during solar vs. non-solar hours

- Hawaii’s load profile is changing as a result of distributed solar generation. Behind-the-meter PV is causing massive swings in utility grid demand that are challenging to accommodate with existing supply options. Distributed solar installations have increased from 12 MW in 2008 to over 300 MW in 2014, and as illustrated in Figure 3, are reaching significant penetration levels. Peak demand now occurs on many days at 7 or 8 pm, rather than the mid-afternoon as was the case historically. Figure 4 depicts this shift in typical load profile that has occurred over recent years as a result of solar installations. Utilities must keep their diesel generators operating during the day in order to reliably meet the night-time ramp in net load and the net-load peak. Akin to California’s “Duck Curve,” which represents the challenges that solar puts on the California electricity grid, Hawaii grid planners have nicknamed their current grid disruptions and challenges due to distributed solar the “Nessie Curve,” inspired by the Loch Ness Monster (see Figure 5 for a daily example).

Figure 3. Distributed PV on distribution circuits on Oahu (August 2015). Left: as a percentage of daytime minimum load; Right: as a percentage of peak load.

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Figure 4. Oahu System Load Profile shift, 2006-2014

Figure 5. Hawaii’s “Nessie Curve”: average 46kV transformer loading, and example of severe system backfeed condition on 8/8/13.

27 See Hawaiian Electric Power Supply Improvement Plan (PSIP) Figure 1-7
Energy storage is well positioned to address many of these challenges, and it is unsurprising that Hawaii’s renewables growth over the past few years has attracted a significant number of energy storage projects. The Hawaiian Electric utilities have recognized energy storage as a key component in their planning. As of the publication of this report, Hawaii has 18 energy storage systems operational totaling 32 MW / 29 MWh, with an additional 3 more under construction totaling 6 MW / 6 MWh under construction.\(^\text{29}\) Notably, several of the Hawaiian utilities have announced plans to deploy additional energy storage capacity.\(^\text{30}\) These projects have been used for testing and demonstrating energy storage capabilities as a tool to reduce costs, integrate variable resources, and maintain system reliability. While the Hawaiian Islands already feature one of the highest concentrations of grid connected battery deployments in the world\(^\text{31,32}\) more storage will be needed to enable and manage the increasing quantities of renewables and help create a truly resilient and clean energy grid. The following four case studies offer an additional lens into the potential benefits of storage at a wide array of deployment sites.

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\(^{30}\) For example, KIUC recently announced a solar plus storage project with SolarCity (http://kauai.coopwebbuilder.com/content/kaua%CA%BBi-utility-signs-deal-solarcity-first-dispatchable-solar-storage-system) and HECO released an RFP for 200 MW of energy storage in April 2014, found here: http://www.hawaiianelectric.com/vcmcontent/StaticFiles/pdf/ESS_RFP_No_072114-01.pdf


CASE STUDIES

1) HAWAIIAN ELECTRIC COMPANY: REDUCING RATES WHILE ENABLING INCREASING SOLAR GENERATION

Case study objective

This case study examines the economic and operational impacts of installing varying levels of distributed energy storage and solar capacity at four different Hawaiian Electric (HECO) distribution feeders. These four feeders together can serve as a representation of the entire electricity system on Oahu. The quantities of solar capacity modeled include both the current level as well as continued growth, up to a scenario where over 80 percent of the feeders' total energy usage is sourced from solar generation. The benefits of these impacts are quantified in terms of HECO capital and operational expenses as well as projected ratepayer impacts.

Key conclusions

Solar (provided at $0.10 per kWh) paired with Ambri’s energy storage can provide over 80% of annual electricity needs, significantly helping HECO achieve its RPS targets, while delivering electricity to ratepayers at a projected average retail rate of $0.24, a 23% percent cost reduction compared to current prices. Table 1 summarizes an incremental four-step plan for achieving an ultimate “Future Energy Scenario” where 83% of demand is met by renewable generation. As solar capacity is added to the system, energy storage levels will increase to enable more consumption of solar and reduce retail rates. The “Future Energy Scenario” envisions a combined solar plus storage resource that provides stable electricity rates over a 20-year (or longer) period at a retail rate equivalent to operating the existing diesel generation fleet with oil priced at approximately $80 barrel\(^{33}\), essentially eliminating Hawaii consumer exposure to world oil market volatility.

From an operational perspective, the combined solar plus storage resource allows for substantially higher levels of solar generation to be consumed than would be possible absent storage, while at the same time reducing strain on distribution network equipment by increasing load factors.

\(^{33}\) This figure represents the average price that Hawaii would pay per barrel, which is typically higher than standard crude oil indices (e.g. Brent crude oil) due to transportation costs and Hawaii’s use of a 60/40 blend of low sulfur fuel oil (LSFO) and diesel for purposes of environmental compliance. See Hawaiian Electric Power Supply Improvement Plan (PSIP), Section F.
Table 1. Simulation results of solar-plus-storage scenarios for a group of four HECO distribution feeders serving a 20 MW peak load.

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Future Energy Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar capacity</td>
<td>3.2 MW</td>
<td>8.1 MW</td>
<td>16 MW</td>
<td>24 MW</td>
<td>40 MW</td>
</tr>
<tr>
<td>Storage capacity</td>
<td>0 MWh</td>
<td>8 MWh</td>
<td>20 MWh</td>
<td>60 MWh</td>
<td>76 MWh</td>
</tr>
<tr>
<td>Projected retail rate</td>
<td>$0.31/kWh</td>
<td>$0.28/kWh</td>
<td>$0.29/kWh</td>
<td>$0.26/kWh</td>
<td>$0.24/kWh</td>
</tr>
<tr>
<td>% Solar + storage (annual generation)</td>
<td>10%</td>
<td>22%</td>
<td>43%</td>
<td>68%</td>
<td>83%</td>
</tr>
</tbody>
</table>

Given the modular characteristics of both solar and storage technologies, HECO would not need to make one large, upfront investment to realize rate benefits. Instead, HECO can make incremental investments in solar and storage, and achieve additional rate reductions after each round of investment. This approach would also enable HECO to get experience and demonstrate results operating solar-plus-storage systems before committing to larger quantities.

Absent investment in storage or other new flexible capacity, HECO will be challenged to continue to integrate levels of solar generation at the growth rates seen today. Energy storage assets will help flatten the “Nessie Curve” by shifting 4-5 hours of production from one period to another, and will mitigate the dramatic frequency fluctuations as well as swings in net load caused by intermittency that would occur if significant levels of solar were added to the grid absent storage. Finally, storage can also serve as an alternative to incremental transmission and distribution infrastructure.

Background

The majority of Hawaiian residents live on Oahu, which is served by Hawaiian Electric, or HECO. In 2014, total electricity sales on Oahu totaled 6,782 GWh, 72% of the state’s total. HECO is subject to many of the emerging “Nessie Curve” challenges described in the introduction due to the recent exponential solar growth on the island; as of December 2014, there were approximately 185 MW of distributed PV capacity in HECO’s Oahu service territory. Roughly 12 percent of Oahu’s electric customers have rooftop solar (compared to a 0.5 percent national average), and adoption continuing to climb. Additionally, the average

34 See introduction for a greater description of the Nessie Curve.
35 The Hawaiian Electric Company serves five islands in the state, and provides electricity for 95% of residents of the State of Hawaii. Maui Electric (MECO) serves Maui, Molokai, and Lanai; Hawaii Electric Light (HELCO) serves the island of Hawaii; HECO serves Oahu.
capacity installed per customer is also growing, as panel costs decrease and more efficient PV panels are installed.\textsuperscript{40}

Conventional generators provide ancillary services including inertia and quick load pickup which provide fast response to help maintain system stability for contingencies such as unexpected generation outages or other system issues. As more non-dispatchable renewable generation displaces these conventional generation sources, system stability can be compromised. Therefore, as increasing levels of solar are deployed,\textsuperscript{41} additional flexible grid capacity must be available to create firm resource capabilities. Additionally, other indirect costs of renewable integration can occur including additional monitoring, data management, controls and renewables forecasting.

HECO provided data for four feeders for analysis in this report; these feeders are a representative snapshot of the various types of distribution feeders on their network, and are summarized in Table 2 below. Additionally, Figure 6 shows how the typical profile can vary from feeder to feeder during September, Hawaii’s typical peak load month.

### Table 2. Characteristics of four HECO feeders analyzed

<table>
<thead>
<tr>
<th>Circuit</th>
<th>PV Nameplate, kW</th>
<th>Peak (Gross) Load, MW</th>
<th>Load Factor</th>
<th>Solar as % of peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit 1</td>
<td>1.015</td>
<td>4.829</td>
<td>45%</td>
<td>21%</td>
</tr>
<tr>
<td>Circuit 2</td>
<td>1.545</td>
<td>5.251</td>
<td>45%</td>
<td>29%</td>
</tr>
<tr>
<td>Circuit 3</td>
<td>0.430</td>
<td>5.535</td>
<td>35%</td>
<td>8%</td>
</tr>
<tr>
<td>Circuit 4</td>
<td>0.225</td>
<td>4.867</td>
<td>38%</td>
<td>5%</td>
</tr>
<tr>
<td>Total</td>
<td>3.216</td>
<td>20.481</td>
<td>41%</td>
<td>16%</td>
</tr>
</tbody>
</table>

**Figure 6: Typical September net load profiles of HECO feeders**

\textsuperscript{40} Ibid.

Methodology

To calculate the net impact of a solar and storage installation to HECO’s system, Ambri energy storage asset operation is modeled with the goals of (1) minimizing peak demand, and (2) maximizing the amount of energy consumed from solar.42

The model uses as inputs:

- Actual hourly load data from four HECO distribution feeders for the 2014 year. These feeders were selected by HECO as together being representative of their larger system, and are located in the greater Honolulu area.
- Hourly solar generation data calculated using NREL’s System Advisor Model (SAM) solar irradiation profile for Honolulu.43

The model considers the following scenarios:

1. Increments of installed solar PV between 1 and 10 MW at each feeder, in increments of 1 MW.
2. Ambri storage systems of between 2 MWh and 20 MWh at each feeder, in increments of 2 MWh.

The outputs from the model are then used as inputs to a broader economic analysis to determine the costs, savings, and projected ratepayer impact for solar-plus-storage scenario modeled. Appendix 4 provides a summary of the step-by-step calculations performed, as well as assumptions that were inputs to the model (e.g., the cost of solar and the cost of storage). Figure 7 below depicts an example four-day result from the operational model.

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42 Operational modeling for this case study uses an alternative spreadsheet-based optimization which is analogous to the Analysis Group RSO model described in Appendix 3, but is configured to allow for the running of a high volume of scenarios.
Figure 7. Example HECO feeder profile with 3 MW of solar. Top: without storage, net load is highly variable and peaks at 1.97 MW. Bottom: 7 MWh of Ambri storage serves to flatten net load, avoid backfeed of excess solar generation, and reduce overall peak net load by 50%.

Results

Deploying solar plus storage yields clear economic benefits to ratepayers. For HECO, there is a point beyond which adding more solar PV capacity without storage will not yield any benefit – solar generation will exceed demand and will need to be curtailed (see Figure 21 in Appendix 1). Storage is instrumental in enabling increasing levels of solar consumption, and its inclusion in the resource mix drives down retail rates. In addition, our results show that energy storage can increase load factor on the HECO system, which can reduce strain on distribution network equipment.

The analysis models an incremental four-step plan with increasing levels of solar plus storage, to achieve a “Future Energy Scenario” where over 80% of electricity needs are met with solar generation. See Table 1. Figure 8 below describes in detail the economics of the “Future Energy Scenario” optimized to maximize the utilization of renewable energy. Results to other scenarios – Steps 1, 2 and 3 – are shown in Appendix 1. With 40 MW of solar (approximately two times gross peak load) and 76 MWh of Ambri energy storage (approximately two times the solar capacity), the four feeders modeled fulfill 83% of annual consumption from renewable generation. Equally important, the increased renewable generation at these four feeders could displace up to 58,000 MWh of diesel fired generation, saving 43,000 metric tons of CO₂ per year.

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44 Base case scenario results shown. Additional scenarios for different fuel pricing and storage cost forecasts are shown in Appendix 1, and a full description of methodology is included in Appendix 4.
45 Based on an oil fired generator with a 10,000 Btu/kWh heat rate.
Assuming these feeders are representative of the entire island of Oahu, HECO could scale such a solar plus storage system to deliver electricity to ratepayers at a projected average retail rate of $0.24/kWh, down from 2014’s $0.31/kWh\(^{46}\). As illustrated in Figure 8, this includes incremental costs for both the solar energy, and associated capital and operation and maintenance expenses for the battery.

**Figure 8. HECO “Future Energy Scenario” (base case results)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost (Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total annual expenses (2014 resources, Sitwell $120/bbl)</td>
<td>$20.0</td>
</tr>
<tr>
<td>Solar cost (solar only)</td>
<td>$3.6</td>
</tr>
<tr>
<td>Reduced diesel (solar)</td>
<td>$7.6</td>
</tr>
<tr>
<td>Flexed capacity investment</td>
<td>$4.0</td>
</tr>
<tr>
<td>Total annual expenses (solar only)</td>
<td>$20.0</td>
</tr>
<tr>
<td>Storage cost (solar only)</td>
<td>$8.4</td>
</tr>
<tr>
<td>Storage O&amp;M (battery charging)</td>
<td>$0.4</td>
</tr>
<tr>
<td>Reduced diesel from storage</td>
<td>$2.2</td>
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<tr>
<td>Avoided T&amp;D expenses</td>
<td>$4.7</td>
</tr>
<tr>
<td>Avoided flexible capacity investment</td>
<td>$1.8</td>
</tr>
<tr>
<td>Total annual expenses (solar + storage)</td>
<td>$16.0</td>
</tr>
</tbody>
</table>

\(^{46}\) Oil prices have decreased from 2014’s values. We evaluate sensitivities to multiple oil scenarios (over a 20 year time horizon) later on in this section, as well as provide full expense breakdown examples in Appendix 1.
Sensitivities

The implications of this case study are robust across a wide range of future uncertainty. Figure 9 presents sensitivities to the base case projected retail rate, including the capital cost of storage, the cost of solar energy, and the price of oil, for which we use Hawaii-normalized EIA projections. At the bottom of Figure 9, we also calculate the projected retail rate of today’s electricity generation mix under various oil price projections for comparison.

One outcome in the “Future Energy Scenario,” since 83% of annual electricity need is met by solar generation, is that ratepayer exposure to oil price volatility is substantially reduced. Projected retail rate varies by only $0.02 from the low ($73 per barrel) to high ($199 per barrel) oil forecasts (between $0.232/kWh and $0.250/kWh respectively). In comparison, today’s electricity generation mix is very sensitive to oil prices; retail rates vary by over $0.20/kWh from the low to high oil scenarios, between $0.223/kWh and $0.428/kWh respectively.

Figure 9. “Future Energy Scenario” sensitivities, shown alongside the sensitivity of today’s generation mix to different oil price forecasts.

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47 Section F of the Hawaiian Electric Power Supply Improvement Plan (PSIP) lays out these forecasts, which take EIA’s forecasts and add certain Hawaii price premiums due to “taxes and certain fuel-related and fuel-handling costs including but not limited to trucking and ocean transport, petroleum inspection, and terminalling fees.” To determine base, low, and high case scenarios for oil prices, we use HECO’s PSIP methodology, but replace the Energy Information Administration’s (EIA) 2014 Annual Energy Outlook with that of 2015, which includes lowered oil forecasts based on recent oil price declines. The result yields an average 20-year oil price forecast of $73, $128, and $199 per barrel for the low, base, and high cases, respectively.
2) **MAUI: MITIGATING CURTAILMENT OF WIND GENERATION**

**Case study objective**

This case study examines the impacts of installing varying levels of Ambri energy storage alongside SunEdison’s 21 MW Kaheawa Wind Power Farm II (KWP II) on Maui. KWP II operates under a power purchase agreement with Maui Electric Company (MECO), but experiences significant levels of curtailment in operations due to transmission security requirements on MECO’s system. Ambri’s batteries will minimize such wind curtailment, and the resulting impacts to various stakeholders are quantified – increased revenues to SunEdison, reduced fuel costs for MECO, reduced costs for MECO to comply with the renewable portfolio standards (RPS), and the societal benefits tied to the value of avoided emissions of carbon dioxide (CO2).

**Key conclusions**

With sufficient energy storage, the current significant levels of wind curtailment on Maui can be avoided. Wind farm owners like SunEdison can increase annual revenues by up to 10 percent, and MECO can more easily reach RPS goals of 100 percent renewable generation by 2045.

Additionally, renewables plus storage could provide MECO a resource mix which would provide stable electricity rates over a 20 year (or longer) period while also providing third party developers with greater economic opportunity, and providing ratepayers with less expensive, stable, carbon-free energy sources.

**Background**

As of the end of 2013, the Maui Electric power system consisted of 243 MW of utility-owned generating capacity, 16 MW of firm capacity produced by independent power producers (IPPs), and 73 MW of variable renewable IPP capacity.48 Like the other Hawaiian islands, the interconnection of distributed solar PV capacity on specific feeders is emerging as a major constraint on customer-sited renewable development, as well as causing substantial curtailment of grid-connected wind generation. In fact, conversations between Ambri and MECO representatives revealed that they see little to no value in adding more solar or wind resources at this time because those new incremental renewable resources would be offsetting other renewable resources rather than diesel generation.

During many hours of the year, any available wind generation in excess of MECO-specified curtailment set points is effectively “dumped,” with curtailment set points established dynamically by MECO in response to overall system supply and demand conditions and system security requirements. While MECO makes efforts to first curtail diesel generation, there are limits to how low the output of firm generators can be turned down and constraints on whether a unit can be fully turned off. For example, MECO must keep enough units online to be able to provide the operating reserves and ancillary services required to run their system. Figure 10 (right) shows an example of how changes in wind output can have a severe effect on grid frequency. As a result, wind generation is often curtailed, which reduces the utilization of SunEdison’s generating assets, lowers their contract revenues, increases the need for generation by MECO’s primarily

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48 Hawaiian Electric Power Supply Improvement Plan (PSIP), p. 4-2.
oil-fired generation fleet, increases emissions of CO₂ and other pollutants, and increases the cost of electricity to MECO's customers by increasing the cost of meeting the company's RPS targets.

In 2013 alone, 46.7 GWh of wind energy were curtailed on Maui, representing 4.3 percent of the MECO’s total of 1,076 GWh sold over the course of the year, and 17 percent of total available wind capacity during that year. During some times of year, wind curtailment can be as high as 50%, as shown in Figure 10 (left).

Figure 10. Left: HECO total wind energy accepted and rejected by time of day. During some hours, curtailment is as high as 50%. Right: Example of wind variability and the effect on MECO frequency.

Based on these challenges, MECO has recognized the value of energy storage, with two of their three wind farms already operating with energy storage. The analysis in this case study goes beyond existing capabilities and studies how additional energy storage capacity can benefit SunEdison, MECO, and Maui customers.

Methodology

To analyze the impacts of addressing this condition through storage installations, the system operational, cost, and emission implications of integrating at the SunEdison KWP II plant are evaluated with a range of Ambri battery installations, in amounts ranging of 5 MWh to 25 MWh, in increments of 5 MWh.

The analysis is performed using one year of 15-minute data supplied by SunEdison, including both the potential output level of KWP II, as well as the actual output level – the difference between the two represents the total wind curtailment. In each storage deployment scenario, Analysis Group’s Renewable

53 Ibid.
54 See Appendix 1 for additional detail on this data.
and Storage Optimization (RSO) model, described in Appendix 3, is used to optimize Ambri’s batteries with the goal of minimizing wind farm curtailment.

Results

Based on current KWP II contract prices and the amount of avoided wind curtailment, the net present value benefit ($2015) of increased revenues to SunEdison at different battery sizes is calculated. The SunEdison results demonstrate substantial benefits associated with the installation of Ambri storage systems co-located at wind farms on Hawaii. As shown in Figure 11 below, SunEdison could receive positive net benefits (NPV) with a battery size of 5-20 MWh. In addition to increasing revenue from avoided curtailment, with increasing battery sizes SunEdison could provide to MECO operating reserves or other ancillary services, though compensation for these services is outside the scope of the current executed power purchase agreement (PPA).

Figure 11. Net Benefits to SunEdison of adding incremental amounts of storage capacity, from 5 MWh to 25 MWh.

Notes and Sources:
[1] Net Benefits are calculated as the difference between incremental SunEdison revenues and total installed battery costs, including levelized capital costs, 7-year MACRS depreciation, and income taxes. Levelized capital costs are based on recovery of investment costs at a 6.40% after tax weighted average cost of capital. Financing costs and benefits are calculated over a 20 year term.
[2] Battery capital costs are estimated at $500/kWh.
**Other Benefits**

In addition to increased revenues to SunEdison, additional benefits flow to MECO, consumers, and society associated with avoided fuel costs, RPS costs, and the value of avoided CO2 emissions. Figure 12 shows both the net revenue to SunEdison and the partial net social benefit at different battery sizes.

**Figure 12. Cumulative benefits of various levels of energy storage**

Notes and Sources:

[1] Net Benefits are calculated as the difference between incremental SunEdison revenues and total installed battery costs, including levelized capital costs, 7-year MACRS depreciation, and income taxes. Levelized capital costs are based on recovery of investment costs at a 6.40% after tax weighted average cost of capital. Financing costs and benefits are calculated over a 20 year term.

[2] Battery capital costs are assumed to be $500/kWh.

[3] Partial Net Social Benefits include the avoided fuel cost of displaced Ultra Low Sulfur Diesel generation (net of the PPA price), the avoided cost of incremental Renewable Portfolio Standard achievement, and the avoided cost of Carbon Dioxide emissions. Marginal RPS costs are assumed to be the levelized cost of rooftop solar. See Hawaiian Electric Companies 2013 Integrated Resource Planning Report, Table K-2(solar prices) and E-117 (fuel prices).

3) **JOINT BASE PEARL HARBOR-HICKAM: PROVIDING ENERGY SECURITY AND RESILIENCY**

Case study objectives

This case study evaluates the reliability benefits of Ambri storage systems for military installations like Joint Base Pearl Harbor-Hickam (JBPHH) in Honolulu, Hawaii. Using JBPHH’s load data across a year, we simulate the use of Ambri storage to achieve grid independence for mission critical load, represented by two different subsets of load at the base: 1) Building 166\(^{55}\) and 2) Hickam Air Force Base. These two loads are analyzed as proxies for potential near- and mid-term goals that might be considered on the path towards full independence of JBPHH from the civilian grid. By installing Ambri storage coupled with onsite generation, JBPHH will be able to operate in the case of an electric utility failure, lower overall electricity spend, and increase consumption from renewable resources.

Key conclusions

Ambri storage can be a cost-effective bridge for the gradual and reliable integration of renewable generation at JBPHH, and for progressively increasing resilience from civilian grid outages, increasing independence from the civilian grid for critical operations.

- Ambri storage would provide critical grid resiliency support for the Base in the event of a civilian grid outage. For example with 50 MW of renewable power and 50 MWh of Ambri energy storage, the Hickam Air Force Base would be self-reliant for electricity for 60 percent of hours per year. 150 MW of renewable power and 200 MWh of Ambri energy storage would enable the Base to provide all of its electricity needs approximately 98 percent of hours.

- JBPHH will be able to harden its infrastructure and ensure reliable electricity delivery to critical loads on the base during emergency periods, while also reducing overall energy spend with storage. For every MW of peak shaving that energy storage achieves, JBPHH can reduce annual energy expenses by $250,000.\(^{56}\) A 50 MWh battery could reduce the JBPHH peak load by an annual average of 6.5 MW, (see Figure 13), reducing Base energy expenses by $1.6 million per year.

- A modular system like Ambri’s will allow the Base to optimally size storage capacity to match growth in renewable capacity over time; that is, as solar PV resources are added to serve JBPHH load, Ambri storage may be added to both increase the benefits of solar additions and smooth out any impact increasing solar has on the distribution system in and around the Base. This will allow the Base to incrementally chart a path towards greater degrees of energy independence for mission critical functions.

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\(^{55}\) Building 166 is a single large non-residential facility on the Base where Ambri has subcontract to Raytheon to deploy a 1MWh energy storage system in 2016 to demonstrate these benefits.

Background

JBPHH is a joint military base in Honolulu, Hawaii home to the U.S. Navy Naval Station Pearl Harbor and the U.S. Air Force Hickam Field. The U.S. Department of Defense (DOD) places a strong emphasis on the importance of resiliency – enabling critical loads to operate in the case of a civilian grid outage. Military installations like JBPHH have unique interests in electricity storage, driven by a desire to minimize energy costs, increase consumption of renewable resources, and create an electric infrastructure that is reliable and resilient in the face of natural disasters or other events. The military has substantial backup generation – usually diesel-fired generation – to ensure sufficient electricity to meet critical mission operations. In addition, the U.S. DOD has a stated objective to reduce diesel emissions and become as energy independent as possible for base and field operations. For example, the U.S. Navy and Marine Corps have a goal of producing at least 50 percent of shore-based energy from alternative sources by 2020.

Thus, JBPHH has a unique interest in exploring the development of renewable resources, and the integration of storage with renewables to simultaneously achieve multiple objectives.

JBPHH is served by Hawaiian Electric Company (HECO) and is a substantial customer for the HECO. The Base has a peak demand of 83 MW, and an annual consumption of over 500 GWh. In 2013, this usage resulted in JBPHH paying over $100 million in energy bills. Over 12 percent of these bills are attributable to demand charges that the base pays to HECO based on monthly peak demand. These charges are significant, at approximately $250,000/MW on an annual basis. Energy storage located at the base would create a powerful opportunity to peak shave and reduce these charges. Figure 13 shows an example where 50 MWh of energy storage is used to reduce peak load in each month, for an average annual savings of 6.5 MW. This peak shaving could save JBPHH $1.6 million of demand charges each year.

57 Analysis Group also provided a detailed assessment of the ability for battery storage technology to enhance the resiliency of power supply at the Joint Base Cape Cod in Massachusetts. They found that 80 MWh of energy storage combined with a total 15 MW of renewable capacity could reduce net critical load (the total level of load that cannot be interrupted, or for which there must be alternative on-site back up generation to ensure continued operations) to just 1 day per year.

Figure 13. JBPHH Load Analysis using 2012 load data demonstrates that a 50 MWh battery could reduce monthly peak by an annual average of 6.5 MW.

Methodology

To calculate the net impact of storage to JBPHH’s operations and energy resiliency, Analysis Group’s RSO model, described in Appendix 3, is used to simulate the operation of Ambri storage on the JBPHH system. The model uses the following inputs, all provided by JBPHH in partnership with this study:

- Annual hourly load data for the full joint base, broken out by Pearl Harbor vs. Hickam loads
- Annual hourly load data for Building 166
- Actual solar irradiation data observed at the base
- One year of monthly HECO electric bills, included tariff and rate structure information

We model the requirements for grid resiliency in two scenarios at JPBH:

1) a single Base non-residential building (“Building 166”) where Raytheon and Ambri are currently planning a micro-grid demonstration project, and
2) the entire load of Hickam Air Force Base (also referred to as the “Hickam-only” case)

For each scenario, the analysis quantifies the number of hours the case locations would need to import power from HECO electricity supply, and at what combinations of renewables plus storage that number is reduced to at or near zero (meaning off-base supply is no longer necessary). We converge on those combinations of renewables and storage that approach energy independence with minimal backup supply.

Results

Ambri’s storage technology, in combination with renewable resources, can enable JBPHH to operate the base absent grid power, insulating mission critical operations from disruptions to the local island civilian grid.

Our analysis demonstrates that JBPHH Building 166 (shown in Figure 14) could approach self-sufficiency with 0.4 MWh of Ambri storage, and between 0.125 and 0.250 MW of renewable generation. Ambri’s project with Raytheon and JBPHH to deploy a 1MWh system to Building 166 is therefore more than
sufficient to provide the necessary resiliency for that building, with extra capacity to spare for neighboring circuits.

For the larger base, resiliency can be accomplished in steps. Hickam for example (shown in Figure 15) could be fully self-sufficient for power approximately 60 percent of hours with 50 MW of renewable power and 50 MWh of Ambri energy storage. The percentage of self-sufficient hours for critical-operations-only will be well above this value, and will depend on the portion of the Base deemed to be critical at any given time. As a longer term scenario, our analysis shows that with 150 MW of renewable power and 200 MWh of Ambri energy storage, the Base could be self-sufficient for power approximately 98% of hours.

Finally, the prevalence of extremely high prices for electricity supply in Hawaii represents both fiscal and operational risks for JBPHH. The results here demonstrate an option for a path forward for the Base that addresses both of these risks – increasing renewable capacity in combination with Ambri storage systems will allow the Base to both reduce electricity costs as well as harden Base electric supply against civilian electric system outages. Build-out of these systems can easily happen in stages given the modular nature of both renewables and storage. As a result, over time more and more critical mission loads can achieve grid independence.
Figure 14. Building 166: Hours with positive net load with various levels of Ambri storage and solar generation.
Figure 15. Hickam: Hours with positive net load with various levels of Ambri storage and solar generation.
4) REDUCING ELECTRICITY COSTS FOR HOTEL AND RESORT CUSTOMERS IN HAWAII

Case study objective

As rates in Hawaii continue to increase, end users have become increasingly motivated to find alternative energy solutions to utility power for some or all of their electricity needs. These alternative energy solutions can be not only more environmentally favorable, but can generate significant cost savings, and mitigate exposure to the possibility of future utility rate increases.

The goal of this final case study is to evaluate the benefits of operating a solar plus storage system at a typical resort hotel in Oahu. The analysis uses load data from a commercial hotel facility in Oahu, alongside various sizes of solar-plus-storage systems in order to reduce energy costs and maximize the amount of electricity consumed from renewable power.

Key conclusions

- **Economic benefits**: Currently, a typical hotel on Oahu pays $0.30/kWh;⁵⁹ with a solar-plus-battery system, the hotel could instead pay an effective rate as low as $0.25/kWh,⁶⁰ representing a 17 percent decrease in costs to the hotel.

- **Renewable potential**: With a solar-only solution, the hotel can achieve no more than approximately 40 percent of its energy from solar; by deploying a storage system alongside PV, the hotel can achieve over 95 percent of its energy from solar power,⁶¹ depending on system size. Notably, “long duration” energy storage is required for such a project to succeed. The battery must have the capacity to charge across 4-8 hours of “over-generation” (when solar capacity exceeds hotel load), and then discharge over the course of the evening as well as morning peak, which can amount to 10-12 hours.

- **System sizing**: The analysis examines the financial and operational impacts of the hotel adding increasing amounts of solar and storage. (The project size will be determined in part based on available real estate.) For each level of solar deployed, the analysis shows an optimum inflection point for sizing a storage system. This optimum maximizes both the net present value (NPV) of the project as well as the percent contribution from renewable energy.

- **Third party opportunity**: Installing solar and storage has clear economic value, with project returns in the 20-25 percent range for a non-leveraged finance structure. This presents an attractive business model for project developers to offer the hotel a combined solar-plus-battery asset under a power purchase agreement (PPA).

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⁵⁹ $0.30/kWh is an average figure, consisting of both demand and energy components of an electric bill

⁶⁰ Assumes capital costs for solar and storage systems are fully debt financed. See Appendix 1 for more details on financing assumptions.

⁶¹ There will always be some hours throughout the year where a back-up generator or grid connection is required, due to periods of sustained cloud coverage. However, the presence of Ambri storage would dramatically lower the need to operate such a back-up system.
Background

The commercial hotel customer modeled for this case study is located in Honolulu, Hawaii, and pays nearly $1 million annually on electricity bills. The hotel has a peak demand around 540 kW and an annual consumption of about 3,200 MWh. Figure 16 shows monthly electricity costs across a recent 12-month period (November 2013 to October 2014), broken out into various bill components.

Figure 16. Twelve months of hotel electricity bills, by charge type

![Figure 16](image)

About 15-20 percent of the bill results from demand charges, which are allocated based on the hotel’s peak power consumption during a fifteen-minute period each month. These demand charges can vary significantly month to month based on peak monthly usage, as seen in Figure 17 below. In order to effectively shave the peak each month, it’s important to understand and predict these load trends. Appendix 1 contains a more detailed discussion the hotel’s energy consumption behavior.

Figure 17. Twelve months of hotel demand charges

![Figure 17](image)
Methodology

To calculate the net impact of a solar and storage installation to the hotel’s expenses, Ambri energy storage asset operation is modeled with the goals of (1) minimizing peak demand, and (2) maximizing the amount of energy consumed from solar.62

The model uses as inputs:

- Actual 15-minute load data from the hotel from November 2013 to October 2014.
- Hourly solar generation data calculated using the NREL SAM solar irradiation profile for Honolulu.63

The model considers the following scenarios:

3. Increments of installed solar PV between 0.75 and 2 MW, in increments of .25 MW.
4. Ambri storage systems of between 0.5 MWh and 10 MWh, in increments of 0.5 MWh.

The outputs from the model are then used as inputs to a broader economic analysis of project Net Present Value (NPV) and annual hotel electricity expenses. A full list of financial assumptions and inputs is included in Appendix 1.

Results

There is substantial economic opportunity for hotels and resorts in Hawaii to reduce their energy costs through solar and storage installations, especially as net metering policies change or perhaps are phased out over time. Solar alone can help reduce grid consumption, but there are limits absent storage: 1) the percent of overall energy use from solar can rarely exceed 30-40 percent, and 2) solar alone cannot be controlled to reduce peak demand charges. With storage, a Hawaiian resort can be almost completely powered by renewable resources, while also providing attractive project NPV to the resort owners.

While the solar installation capacity of a downtown Honolulu hotel is limited by space constraints, many of the Hawaii resorts that are outside of Honolulu have plenty of space to maximize solar usage. For example, solar canopies over parking lots would be an attractive location for such systems.

Figure 18 and Figure 1964 show the analysis outputs for percent renewable energy and overall project NPV under each combination of solar-plus-storage scenario. Each line represents a different level of solar MW deployment, with the x-axis representing the MWh of storage. For example, with 1.5 MW of PV and 4 MWh of storage, the hotel can consume approximately 77% of its energy from solar at a project NPV of $4.1 million.

These graphs can be used to help hotel decision makers to determine the optimal solar plus storage system size to maximize renewable energy consumption and project returns.

62 Operational modeling for this case study uses an alternative spreadsheet-based optimization which is analogous to the RSO model, but is configured to allow for the running of a high volume of scenarios.
64 Base case inputs use $500/kWh as the cost of storage, and a 100% debt financing. See Appendix for additional details.
Figure 18. Total renewable energy consumption at various levels of solar and storage capacities.

Figure 19. Project NPV at various levels of solar and storage capacities.\textsuperscript{65}

The components of the hotel's annual expenses under a scenario with 1.5 MW of solar and 4 MWh of storage are shown in Figure 20. With this solar and storage system, the hotel can significantly reduce annual electricity expenses. As a base case, we assume that the project is fully leveraged, with storage costs at $500/MWh; additional annual expense breakdowns based on differing storage costs and debt financing options are including in Appendix 1.

\textsuperscript{65} NPVs include a 30\% Investment Tax Credit (ITC). See Appendix 1 for NPVs using the post-2016 ITC of 10\%. 
Figure 20. 1.5 MW of solar and 4 MWh of storage; 100 percent debt financed (base case)\(^{66}\)

\[^{66}\text{See Appendix1, Figure 31 for additional projected retail rate scenarios.}\]
APPENDIX 1. ADDITIONAL SELECT INFORMATION ON SPECIFIC CASE STUDIES

Case 1: Hawaiian Electric Company: Reducing rates while enabling increasing solar generation

Figure 21. Base case annual expense reductions demonstrate diminishing returns of solar-only capacity build-out, as compared to ongoing and greater benefits of solar-plus-storage resource additions. Storage sized optimally based on level of solar in each scenario.

Figure 22. Step 1 towards HECO future energy scenario
Figure 23. Step 2 towards HECO future energy scenario

Figure 24. Step 3 towards HECO future energy scenario
Figure 25. HECO future energy scenario (high oil case: 199/barrel)

Figure 26. HECO future energy scenario (low oil case: $73/barrel)
Figure 27. HECO future energy scenario (high storage case: $1000/kWh)
Case 2: Maui: mitigating curtailment of wind generation

Figure 28: Box plot of KWPII curtailment by hour of day across April 2014. Majority of curtailment overnight and during peak solar generation hours.

Figure 29: Detailed KWPII availability, output, and curtailment levels over three day period in April 2014.
Case 4: Reducing electricity costs for hotel and resort customers in Hawaii

Table 3. Financial inputs and assumptions for Base Case model

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<th>Input</th>
<th>Value</th>
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</tbody>
</table>

Figure 30. Net Present Values using 10% Investment Tax Credit (ITC)

Further analysis of the hotel’s load data was also used to help determine appropriate operating parameters for Ambri’s battery system and is discussed in this section.

As seen in Figure 32, summer and fall contain the hottest and muggiest months of the year in Hawaii, causing the hotel to have its highest load during these months, along with the greatest opportunity for peak shaving. The large jump between seasons is also a clear reminder of how increasing air conditioning loads will continue to decrease load factors in Hawaii in the future.

There are also trends by day of the week. Figure 33 shows that Sunday is the lowest load day, possibly related to lower occupancy levels, while Friday is the highest load day, and therefore a time to focus on peak shaving. Also noticeable is that the daily peak is usually in the morning (with the exception of

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68 Uses base case inputs listed in Table 3.
September), so it’s important to make sure the battery remains charged enough overnight to lower the morning peak, even on cloudy days when the solar cannot be used to reduce peak demand.

**Figure 33. Weekday variability of hotel load.**
APPENDIX 2. SPECIFICATIONS OF AMBRI’S LIQUID METAL BATTERY

Ambri technology background

The Ambri energy storage system is based on a new type of battery cell technology known as the “Liquid Metal Battery” (LMB). The LMB has an all-liquid design with three active components – two metal electrodes separated by a molten salt electrolyte. Cells operate at elevated temperature and the three layers self-segregate and float on top one another due to their different densities and levels of immiscibility. The battery operating mechanisms are described in detail in Figure 34. Battery electrode materials are selected for high voltage capability and low cost.

Ambri highlights a number of advantages associated with its technology – compared to many other battery storage devices – from the perspectives of flexibility, economics, power system operation and reliability, and safety. The battery cell is simple, uses earth-abundant materials, and the all-liquid design avoids the main failure mechanisms experienced by solid components in other battery technologies. Also, battery chemistry and the lack of solid or moving parts mean that the Ambri battery can maintain efficiency and operability for a very long time.

Figure 34. Operating mechanisms of the Ambri battery cell.
The Mg||Sb chemistry is illustrative and not the chemistry Ambri is commercializing; Ambri is commercializing a chemistry that is lower-cost and higher voltage. The LMB operates at close to 500°C. In a charged state, there is potential energy between the top metal layer and the bottom metal layer which creates a cell voltage. To discharge the battery, the cell voltage drives electrons from the Mg electrode, delivering power to the external load (e.g., light bulb), and the electrons return back into the Sb electrode. Internally, this causes Mg atoms to shed electrons and dissolve into the electrolyte as positively charged ions, then pass through the salt and alloy with Sb, forming an Mg-Sb alloy. To recharge, power from an external source (e.g., wind turbine) pushes electrons in the opposite direction, pulling Mg from the Mg-Sb alloy, forcing it through the electrolyte as an ion, and re-depositing Mg back onto the top layer, returning the system to three distinct liquid layers.

69 The description of the Ambri battery and its expected operational characteristics and performance presented in brief in this section come directly from Ambri. They are based on public Ambri materials and studies, as well as Analysis Group discussions with Ambri employees. Additional information on the capabilities, status and prospects of the Ambri storage technology may be found on the Ambri website (www.ambri.com) or by contacting the company.
Perhaps most importantly, the Ambri battery can be operated primarily as a source of capacity, a source of energy, or both. It can change from charge to discharge state in milliseconds, allowing it to qualify as a fast responding resource to meet power system reserve, load following, and frequency regulation needs, and enabling it to efficiently and effectively balance the variability of renewable resources. This capability is in addition to the ability to store large amounts of energy over longer periods of time, allowing it to simultaneously be used to (1) help meet system frequency, voltage, and stability needs from instant to instant, (2) follow load during system ramps on the order of minutes and hours, and to shift net load from peak to off-peak periods, and (3) capture excess low-variable cost renewable power to either prevent the wasting of otherwise-curtailed energy or sell such power when its value is highest. This capability is illustrated hypothetically in Figure 35.

**Figure 35. Ambri's battery systems can provide simultaneous capabilities to the electric grid.**

The Ambri battery cell is the base building block of the Ambri system; cells are aggregated so that installations may be sized to optimally meet reliability or economic objectives. The modular nature of the battery allows for repeatable manufacturing and easy transport. Generally, 768 Ambri cells are aggregated into Ambri Cores of 200 kWh. These may be further aggregated into a full Ambri System of 1 MWh, including 5 Ambri cores and associated power electronics.
Figure 36. Commercial 1 MWh Ambri System Architecture.
Cells are stacked together into Cores, five of which make up the base Ambri System that is 1 MWh in capacity, modular, and easily strung together to create larger energy storage systems.

System specifications
When modeling battery operations, Analysis Group used the following system specification inputs:

- Energy-to-power ratio modeled as 2:1 at peak power
- Response time: < 10 milliseconds
- Ramp rate: 200 MW/s
- C-rate and efficiency specifications as follows:

<table>
<thead>
<tr>
<th>C-Rate</th>
<th>Roundtrip DC-DC efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/2</td>
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<tr>
<td>C/12</td>
<td>0.89</td>
</tr>
</tbody>
</table>
APPENDIX 3. ANALYSIS GROUP’S RENEWABLE/STORAGE OPTIMIZATION MODEL

The quantitative valuation is carried out in part through Analysis Group’s Renewable & Storage Optimization (RSO) model, combined with various post-processing calculations based on model output. RSO outputs are then also used by Ambri to carry out its economic analysis. The RSO tool is designed to allow for a review of battery use under different combinations of load/generation and battery size, different market contexts, different rate structures, and different economic objectives. In this study, RSO analyses are tailored to the specific system/load/generation conditions of the case studies, and the model optimization is set to meet project case study objectives.

The value streams that flow from storage operations in these various contexts depend significantly on optimizing the combined renewable generation capacity and storage technology with electrical load characteristics (both peak and energy). The model is used to account for the flexibility of the Ambri battery technology, and the model allows the user to tailor battery operation to optimize on the user’s specific objectives (e.g., minimize electricity costs; minimize curtailment output and maximize revenues; eliminate or minimize backup diesel generation; etc.). Consequently, we structure the case studies and modeling tasks to find these optimums by exploring a range of potential configurations in each case, representing various combinations of levels of generation and curtailment; electrical demand levels and shapes; mix/quantities of installed renewable resources; and various amounts of installed Ambri storage capacity. The various ranges of scenarios are presented in the summaries of case study analyses presented in the main body of the Report.

Analysis Group developed the RSO model to analyze the potential value of a wide range of different storage technologies – with different operational and efficiency profiles – in a variety of utility jurisdictions, wholesale markets and retail service settings. Applications of the model can be tailored to analyze optimum storage technology applications across a number of different contexts and conditions. These include different storage technology characteristics and operating modes; different customer segments; different electric industry and market structures; different conditions by state and region; different load and generation characteristics; and different functional and economic objectives of the host site. These are shown in Figure 3 below.

In this Report we review expected benefits in part by modeling Ambri battery operations across several case studies in Hawaii selected and designed to explore a cross-section of potential values streams, and quantifying associated costs and benefits. For the purpose of running the Analysis Group optimization model, we apply battery cost market data provided by Ambri, with a base value of $500/kWh and sensitivities reviewed for $250/kWh and $750/kWh cases. This Appendix summarizes the Analysis Group model approach and results; however, model outputs are also used in the economic analyses developed by Ambri, and presented in the main body of the Report.

70 We have not independently reviewed Ambri’s expected storage cost; however, Ambri expects that the costs used for our analysis is appropriate for the evaluation of Ambri storage economics.
Figure 37. Inputs, optimization criteria, and outputs of Analysis Group’s Renewable & Storage Optimization (RSO) model

Note: Wholesale benefits are not calculated for the Hawaii case studies presented in this report.

Once configured, the RSO model evaluates storage technology value through simulations of battery-use optimization. The optimization examines load, generation, price, and tariff data, subject to constraints on battery operations and pursuant to user optimization objectives. The optimization solves for hourly battery operation modes (charge, discharge, rate, endpoint) that meet the optimization objective over the selected time period (e.g., one month). In effect, for a given set of load, generation, and battery technical specifications, the ROS model will identify hourly (8,760) levels of charge and discharge that result from meeting the user’s optimization objective (e.g., minimize retail charges for electricity; minimize generation curtailment). Model output includes a number of metrics of interest to the user – such as adjusted load, total costs with/without storage; monthly and daily charts of battery use and results; and comparisons of results across multiple scenarios.

**General Configuration of the RSO Model for the Hawaii Case Studies**

The Project Imua case studies are each different in a number of ways, but they all fundamentally involve three main elements, presented or calculated for a representative model year:

1. **Inputs: System Representation:** Each case study – and each scenario run for each case study – begins with a representation of electric system circumstances, involving identification or estimation of:
   a. Hourly load;
   b. Hourly generation supply, including existing and/or postulated quantities of new renewable resources where relevant for the case study and scenario;
   c. Ambri energy storage (in MWh of capability); and
   d. Various financial/pricing inputs associated with the cost of power, price of fuel, cost of renewable resources, cost of battery installations, etc.
2. **Outputs: Scenario Battery Utilization and Associated System Changes:** Applying the inputs, subject to the user-selected optimization objective (e.g., minimize retail electricity costs), the model generates:
   a. Hourly battery use (rate and quantity of charge and discharge) and state of charge;
   b. Changes (increases) in generation output that result from operation of the battery in combination with associated generation resources; and
   c. Changes (if relevant) in “net load” (amount of electricity purchased or generated from the surrounding grid) that result from operation of the battery in combination with associated generation resources.

3. **Impact Metrics:** Using the outputs described above, the model (and related post-processing routines) calculates benefits and costs associated with differences between scenarios with Ambri batteries installed, versus the “base case” with no battery installed. Depending on the scenario this could involve one or more of the following:
   a. Change in end-user energy consumption, peak load, and costs of electricity;
   b. Reductions in quantity of fuel oil consumed, and associated fuel cost savings;
   c. Increase in usable renewable resource output (i.e., in excess of constrained amounts due to battery utilization);
   d. Additional revenues to renewable generation owners;
   e. Number of hours, days, and total quantities of energy obtained from off-site suppliers of electricity;
   f. Costs associated with the installation of the scenario’s postulated quantities of renewable power and battery storage capacity;
   g. Avoided costs for incremental renewable resources needed to meet renewable portfolio standards;
   h. Avoided emissions of CO2 and the value of such avoided emissions based on estimates of the social cost of CO2; and
   i. Various representations of net benefits or net costs associated with the scenario.

Operational modeling for the HECO and hotel cases was developed through an alternative spreadsheet-based optimization analogous to the RSO model, but configured to allow for the running of a high volume of scenarios.
APPENDIX 4. HECO FINANCIAL MODEL DETAILS AND DISCUSSION

General Configuration of the Economic Model

This appendix is a discussion of the economic analysis and assumptions involved in the HECO case study. The analysis quantifies the impacts on HECO’s annual expenses of an investment in a solar plus storage resource. Figure 38 summarizes the analytical framework: the costs and benefits of a solar plus storage investment are netted from (A) HECO’s total annual expenses for 2014, which includes operational and capital expenses. Costs are in red; benefits (i.e., reductions in costs) are in green.

The analysis uses 2014 as a baseline year, and begins by examining the impact of additional investment in solar without energy storage. There are three impacts due to solar: (B) variable energy cost of directly consumed solar generation, (C) reduced diesel consumption due to solar, and (D) additional required flexible capacity investment due to solar. These three impacts produce (E), HECO’s projected annual expenses under a solar-only scenario.

From there, the analysis calculates the impact of complimenting solar with energy storage. There are three additional costs associated with energy storage: (F) storage annualized cost, (G) storage operations and maintenance (O&M) costs, and (H) the variable energy cost of solar used for battery charging; in addition, there are three additional sources of cost reduction: (I) reduced diesel consumption due to storage, (J) avoided transmission and distribution (T&D) expenses, and (K) avoided new flexible capacity investments. Items F through K are then netted from E to produce (L), HECO’s projected annual expenses including the impacts of both solar and storage on the system.71

Figure 38. HECO total annual expenses methodology.

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71 This financial analysis is performed as a broad and high level quantification of the impacts of energy storage on HECO’s system. In order to understand in detail the full impact at any given location on the HECO grid, a full engineering study will be necessary.
A. **Total annual expenses (2014 resource mix):** The analysis begins with the 2014 year as a baseline, and breaks down HECO's total expenses on a pro-rata basis to determine the portion attributable to the four feeders analyzed, which are meant to be representative of HECO's larger system.\(^2\)

B. **Solar cost (direct consumption):** This is the variable cost of solar generation that is consumed directly ("direct solar"); does not include solar that is stored in Ambri's battery for use at a later time ("time-shifted solar").

C. **Reduced diesel from solar:** This is the avoided fuel cost of diesel due to “direct solar” consumption (this excludes any reduction in diesel costs from “time shifted solar”).

D. **Flexible capacity investment:** As solar penetration increases, there is an investment needed to support the ramping requirements and frequency deviations caused by solar. The current cheapest source of peaking flexible capacity would be a single cycle combustion turbine, so while other technologies like combined cycle turbines could also provide this capability, we chose to use the least cost option for our modeling.\(^3\)

E. **Total annual expenses (solar-only):** This is the resulting HECO annual expenses from an investment in solar generation, calculated as (A) plus the impacts of (B), (C) and (D).

F. **Storage cost:** This is the annualized payment towards storage capital costs, using HECO-specific weighted average cost of capital (WACC).

G. **Storage O&M:** This is the annual O&M expenses associated with storage, including software upgrades, battery pack replacements and other routine maintenance. For this we use the Ambri-specific value of $5000/MWh.\(^4\) Due to the simple nature of Ambri’s batteries and lack of moving parts, this figure is expected to be lower than other battery storage systems.

H. **Solar cost (battery charging):** This is the variable cost of time-shifted solar – that is, the cost of solar that is purchased and stored in Ambri's battery for use at a later time. This figure includes the efficiency loss from the battery.

I. **Reduced diesel from storage:** This is the avoided fuel cost of diesel due to solar energy that is stored and later discharged for use.

J. **Avoided T&D expenses:** Optimal operation of storage enables an improved load factor and reduced peak demand on HECO's system; this results in a reduction of fixed transmission and distribution (T&D) expenses. See the following page for a more detailed discussion of this benefit.

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\(^2\) To calculate baseline annual expenses for the four feeders analyzed, we remove the operating margin component of the 2014 average retail rate of $0.315/kWh to calculate an effective overall cost per kWh of $0.297. The 2014 HECO operating margin was 6.05%, as reported in the company's FERC Form 1 filing. The average 2014 retail rate of $0.315 is calculated by averaging the monthly reported values from Hawaii's Department of Business, Economic Development & Tourism (DBEDT) monthly report available at [http://files.hawaii.gov/dbedt/economic/data_reports/energy-trends/Monthly_Energy_Data.xlsx](http://files.hawaii.gov/dbedt/economic/data_reports/energy-trends/Monthly_Energy_Data.xlsx). Total 2014 expenses for the four feeders are then calculated by multiplying the total annual kWh usage by the effective cost of $0.297/kWh. In examples showing alternative oil price scenarios, the additional cost or savings difference is divided equally across expenses to determine an updated effective cost per kWh.

\(^3\) To determine the quantity of flexible capacity investment required, we assume that 50 percent of any solar capacity above current levels will require additional dispatchable, flexible capacity to accommodate intermittency and ramping needs. The actual amount of flexible capacity required will vary from system to system and can be determined by further detailed engineering analysis and resource planning. California recently has developed flexible capacity requirements, and for 2015 determined that 11 GW of flexible capacity will be required (see Figure 3, [http://www.energy.ca.gov/renewables/ tracking_progress/documents/resource_flexibility.pdf](http://www.energy.ca.gov/renewables/tracking_progress/documents/resource_flexibility.pdf)) for a projected total of 15.8 GW of intermittent resources (see Table 1, [http://www.caiso.com/Documents/DraftFinalProposal-FlexibleResource AdequacyCriteriaMustOfferObligation.pdf](http://www.caiso.com/Documents/DraftFinalProposal-FlexibleResourceAdequacyCriteriaMustOfferObligation.pdf)), indicating that 70 percent of nameplate renewable capacity is required in corresponding flexible capacity.

\(^4\) Value calculated and supplied by Ambri.
K. **Avoided flexible capacity investment**: Ambri’s storage contributes to meeting the ramping requirements and mitigating the frequency deviations caused by solar and can serve to avoid some or all of the additional flexible capacity investment from item (D).

L. **Total annual expenses (solar and storage)**: This is the resulting HECO annual expenses from adding storage to an investment in solar, calculated as (E) plus the impacts of (F), (G), (H), (I), (J), and (K).

**HECO specific inputs**

In order to accurately calculate the impact of solar plus storage on HECO’s unique system, modeling inputs and assumptions were determined working in conjunction with HECO’s representatives. All of these inputs leverage existing information, drawing heavily from HECO’s 2014 Power Supply Improvement Plan (PSIP)\(^75\) as well as the company’s 2014 FERC Form 1 filing.

- Weighted after tax average cost of capital (WACC): 8.076 percent\(^76\).
- Cost of new flexible capacity: We use the 2020 value of $2,130.91/kW for a simple cycle combustion turbine on Hawaii\(^77\).
- Transmission and Distribution (T&D) savings: Today, utilities build electric systems to meet reliability requirements in all hours, including during peak demand conditions; peak demand conditions are not common, and the result is that much of the T&D capacity is only fully utilized a fraction of the time. It is possible to optimize a storage asset such that the T&D system is operated more efficiently, and thus avoid or defer other T&D infrastructure investments. Using HECO’s 2014 FERC Form 1 filing,\(^78\) we itemize annual balance sheet investments as well as annual O&M expenses for T&D. In 2014, HECO spent $193.0 million on new T&D investments,\(^79\) and $63.4 million on T&D specific O&M costs for a total of $256.4 million costs associated with T&D. These T&D expenses imply a fixed cost per MW of $164,000 based on HECO’s combined non-coincident system peak of 1,564 MW.\(^80\) We assume that by optimally operating energy storage, HECO can reduce peak demand at the feeder level and improve load factor, thus reducing future costs by $164,000 for every MW of peak demand reduced.\(^81\)
- Average price of oil in Hawaii (per barrel) over the next twenty years: We use HECO’s PSIP methodology, but replace the Energy Information Administration’s (EIA) 2014 Annual Energy Outlook

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\(^75\) Hawaiian Electric Power Supply Improvement Plan (PSIP).

\(^76\) Hawaiian Electric Power Supply Improvement Plan (PSIP), Table F-1

\(^77\) Hawaiian Electric Power Supply Improvement Plan (PSIP), Table F-10.


\(^79\) This $193.0 million that HECO spent in 2014 on T&D investments is about 8% of its total T&D asset base, which is reported to be $2.6 billion in 2014.


\(^81\) Transmission and Distribution investments are typically driven by location and hourly specific needs, which may or may not be coincident with solar or storage technology that is sited to maximize energy production. Previous studies have acknowledged the unique challenge of quantifying these benefits. [See, for example, Energy + Environment Economics, “Evaluation of Hawaii’s Renewable Energy Policy and Procurement” Final Report, January 2014, page 18, available at http://puc.hawaii.gov/wp-content/uploads/2013/04/HIPUC-Final-Report-January-2014-Revision.pdf]. Here, we present a representative estimate of avoided T&D benefits based on HECO annual T&D investment and operating expenses. An alternative estimate could consider the avoided capacity benefits that account for generation and transmission/distribution investments and rely on the values provided in the Hawaii Energy Technical Reference Manual. These savings should be adjusted downward to account for HECO’s cost of capital and necessary carrying charges, which will tend to reduce the annual and total cost of capital expenditures. Actual savings to HECO could be higher or lower depending on the site specific T&D infrastructure needs.
with that of 2015, which includes lowered oil forecasts based on recent oil price levels. See the sensitivities section of the first case study for a more detailed discussion of oil pricing assumptions.

Table 4. Additional HECO case study solar and storage cost inputs and sensitivities reviewed.

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<thead>
<tr>
<th>Input</th>
<th>Base value</th>
<th>Sensitivities reviewed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capital cost ($/kWh)</td>
<td>$500</td>
<td>$250; $750; $1000</td>
</tr>
<tr>
<td>Solar cost ($/kWh)</td>
<td>$0.10</td>
<td>$0.08; $0.12</td>
</tr>
<tr>
<td>Storage annual O&amp;M (/MWh-yr)</td>
<td>$5,000</td>
<td>$2,500; $7,500</td>
</tr>
</tbody>
</table>

82 This is the fully-installed system cost, including the DC-DC battery system, required power electronics, grid interconnection costs and costs associated with engineering and construction.