Project Vigilance

Functional Feasibility Study for the Installation of Ambri Energy Storage Batteries at Joint Base Cape Cod

Analysis Group

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Joint Base Cape Cod

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The report, however, reflects the analysis and judgment of the authors only, and does not necessarily reflect the views of the Commonwealth of Massachusetts, Ambri, JBCC or Raytheon.

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 modeling and 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.

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1. EXECUTIVE SUMMARY

Background

Economic storage of electricity has the potential to dramatically transform the energy industry in the coming decades, shifting generation sources, system operations, revenue flows, consumer costs and ratemaking structures in fundamental ways. Storage can help consumers address energy costs, large users and municipalities achieve security and resilience of supply, utilities avoid costly distribution system infrastructure upgrades, and regional power system operators more reliably and efficiently manage the increase in net load variability that comes with increased penetration of variable renewable resources.

From a policy perspective, the pursuit of economic storage opportunities is driven by the need to achieve or manage several interrelated policy mandates. These include: (1) the convergence of state and federal policies to begin addressing climate change risks, and expand renewable generation; (2) the proliferation of variable wind and solar generation resources in front of and behind the end-user's electric meter, with economics that are achieving or approaching grid parity for some technologies in some settings; (3) the transformation of aging power system generation and delivery infrastructure, including the potential retirement of many of the country's fossil power plants and increased decentralization of power system resources; and (4) the pressing need to effectively and economically manage substantial increases in power system net load variability in many regions. System operators, utility managers, resource developers, state and federal regulators, and energy officials are considering these emerging trends and evaluating technologies that can help manage a fundamental transition in power system operations and economics. There is movement toward developing new cost structures and regulatory policies that are a better fit for a modernized grid.

The Commonwealth of Massachusetts has been a national leader in many of these areas and – along with similar policies in neighboring states – the New England power system is undergoing major change. Demand growth has been attenuated and has become more uncertain by aggressive policies to increase energy efficiency investments and spur the installation of net metering renewable resources behind the meter. Significant growth in grid-scale wind and solar photovoltaic capacity is emerging as an important bulk power system feature due to renewable portfolio standards, utility build, and long-term contracts for renewable resources. And the emergence of low-variable cost renewables plus low and stable natural gas prices have created economic conditions accelerating the retirement of older fossil-fuel and even nuclear generating capacity.

Massachusetts has also been a leader in seeding and facilitating the growth of emerging advanced energy technologies, such as storage. Massachusetts has supported these technologies through research and development funding and other policies aimed at moving local, clean technology products from the laboratories to commercial success. This report is part of a project funded in part by the Commonwealth of Massachusetts with exactly this goal.

This study is a Functional Feasibility Study (FFS), funded under a grant by the Massachusetts Clean Energy Center (MassCEC) to assess the value and explore the potential development of a Massachusetts-based advanced electricity storage technology, to consider how storage may support critical military objectives and reduce end-user costs at the State's largest military base, and to assess how storage may help integrate substantial renewable installations in wholesale and retail electricity market settings.

In May of 2013, the MassCEC selected Project Vigilance – including this initial FFS – for funding under the InnovateMass Program. The goal of Project Vigilance is to demonstrate the liquid metal battery (LMB) storage solution under development by Cambridge-based Ambri at Joint Base Cape Cod (JBCC).

The JBCC is a unique end-use location for storage demonstration since it combines high electricity demand, significant variable renewable resource development, and mission-critical functions requiring high quality and security of supply. The Project Vigilance storage demonstration will proceed in two phases, ultimately resulting in deployment of Ambri LMB systems at a scale of megawatt-hours (MWh) of energy storage. Deployment will be initially at JBCC, and possibly at other site(s) to be facilitated by Massachusetts Development Finance Agency (MDFA). Phase I – which is funded in part by the MassCEC InnovateMass Program – includes this FFS plus the initial prototype deployment at JBCC.

Study Purpose and Structure

This FFS investigates the reliability, security and energy/environmental policy value of Ambri's storage technology, and the economic value of various levels of storage installation on site at JBCC. In short, the analysis is structured to test the following questions and expectations:

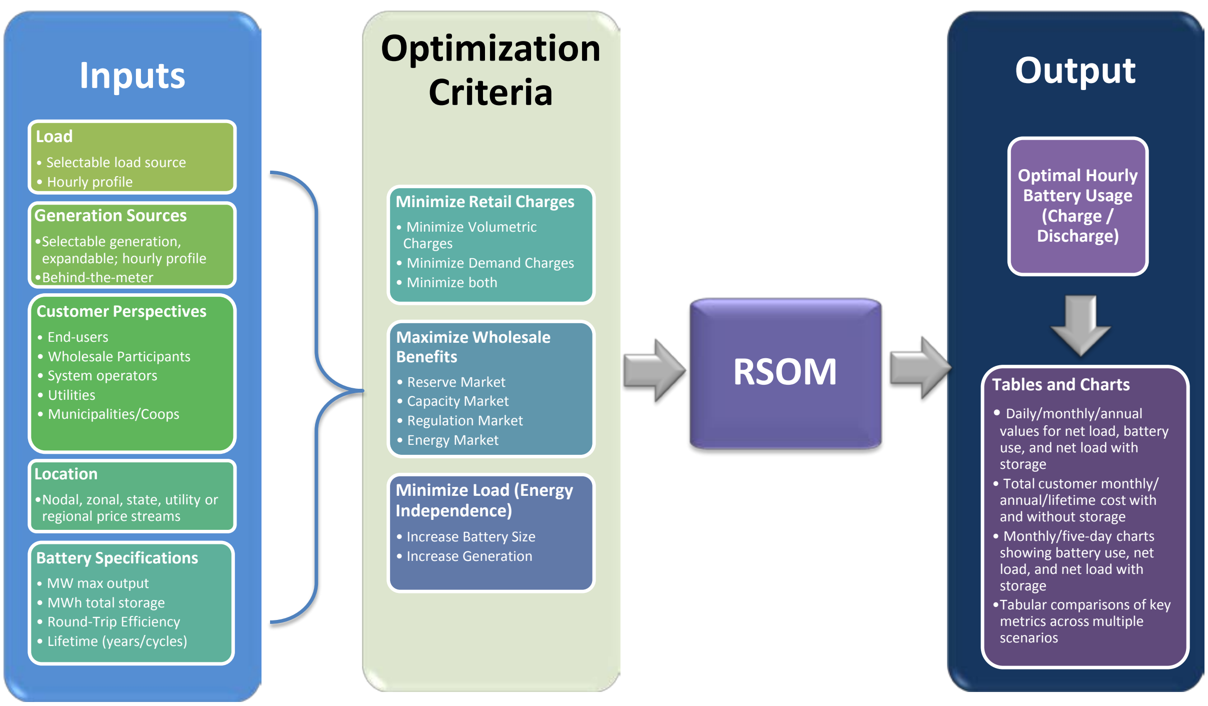
- Can Ambri's LMB storage technology benefit the Commonwealth's energy and environmental policy goals?
- Can installation of Ambri batteries at JBCC generate meaningful cost savings for JBCC as a retail end-use customer, and what factors affect this outcome?
- Can Ambri's storage support more economic integration of current and/or expanded installations of renewable generation (primarily wind and solar) at JBCC (and in similar settings)?
- Can Ambri batteries enhance the resilience of power supply for JBCC's critical mission activities if separated from the surrounding power grid? What combinations of generation and Ambri batteries would maximize resilience of critical mission activities in the most economical fashion?
- Can Ambri's technology enhance New England and local power system reliability?
- What is the value of Ambri batteries – alone or in combination with traditional and/or renewable generating assets – in regional wholesale electricity markets? How might emerging federal market policies or retirement of nearby power plants (e.g., Canal) affect this?

The study was structured to answer questions about the value of Ambri's storage technology in two contexts: First, what is the value in military applications using actual data related to specific electricity generation consumption, and mission critical activities at the Commonwealth's largest base, JBCC? Second, what is the broader reliability and economic value of Ambri's storage technology in the wholesale market context, and considering the energy and environmental policies and goals of the Commonwealth?

Analytic Method

The core of the analysis in this study uses Analysis Group's Renewable & Storage Optimization Model (RSOM). Analysis Group developed the RSOM tool to analyze the potential value of a wide range of different storage technologies – with different operational and efficiency profiles – in a variety of possible wholesale market and retail service settings. Applications of the model can be tailored to analyze optimum storage technology application across a number of different contexts and conditions, including: (a) storage technology characteristics and operating modes; (b) customer types or market participants, and customer priorities and objectives (e.g., wholesale versus retail; cost versus security); (c) market or industry structures (competitive/merchant and/or integrated/regulated); (d) states, regions, or control areas; (e) characteristics of customer or utility/regional load (magnitude, variation over hours/days/months); and (f) mixes of generation resources.

Figure E1: Analysis Group's Renewable & Storage Optimization Model (RSOM) Flow Chart



The model uses a constrained optimization process to solve for optimal battery operation on an hourly basis, subject to user-input data (on hourly load, generation, etc.) and constraints (on storage technology specifications, optimization objectives, etc.). The model automatically generates hourly data on load, generation, net load, battery usage, and battery-net load (i.e., load net of generation and battery use); and generates charts and metrics of interest with respect to customer costs, resilience of supply, and battery operations. See Figure E1.

The scope and method of analysis in this study were selected to explore potential value streams across many potential applications of Ambri batteries at JBCC. The RSOM tool was configured with hourly JBCC load and generation data, applicable tariffs of the local distribution utility (Northeast Utilities) that serves the base, hourly zonal wholesale prices, and several different combinations of Ambri battery sizes and optimization objectives. In addition to modeling analysis, we review qualitatively additional potential benefits of Ambri's technology from system reliability, efficiency and state/federal policy perspectives. Specific areas of potential benefits reviewed in this study qualitatively or modeled and quantified using RSOM are presented in Table E1.

Table E1: Potential Battery Benefits and Model Approaches

Battery Value	Perspective	Description	Model Approach
Retail Costs	End-use customer	Battery used to minimize all-in cost of electricity	Apply constrained optimization on battery use to minimize customer monthly bills
Critical Load; Resilience & Independence	End-use customer	Battery used to protect critical end-use operations against transmission or distribution outages, or minimize use of back-up generation	Iterative application of battery optimization to minimize hours with net positive critical load
Energy Market Arbitrage	End-use customer or wholesale market participant	Available battery storage capability used to maximize the daily/weekly value of generation in energy market	Apply constrained optimization on battery use to maximize energy market revenues (and/or minimize wholesale energy costs) considering base generation resources and load
Capacity Market Revenues	End-use customer or wholesale market participant	Battery used in power/capacity mode to gain revenues in capacity market	Calculate annual capacity market revenues under different market forecasts
Reserve Market Revenues	End-use customer or wholesale market participant	Battery used in power/capacity mode to gain revenues in reserve market	Calculate annual reserve market revenues based on historical reserve market prices
Regulation Market Revenues	End-use customer or wholesale market participant	Battery capability offered as a regulation resource	Calculate annual regulation market revenues based on average historical market prices
Deferral of Infrastructure Investment	Transmission or distribution utility	Strategic placement of battery storage to support local system reliability	Discuss qualitatively
Power System Reliability and Efficiency	Regional power system operator, wholesale customers	Integration of storage to improve the reliability and efficiency of managing power system peak loads, load-following, and reserve requirements	Discuss qualitatively
Integration of Renewable Resources	Public Policy	Facilitate greater use of low/zero carbon resources to meet state or federal policy objectives; reduce need for traditional peaking resources to balance variability	Iterative application of battery optimization to reduced use of backup generation at increasing levels of renewable integration; discuss qualitatively

Results and Observations

Our review was designed to answer a number of key questions related to the benefits of Ambri's storage technology in general, and related to the potential value to JBCC from cost and security perspectives in particular. While the analysis is rooted in actual historical data from JBCC on hourly loads and generation, from applicable distribution system tariffs, and from New England wholesale markets, and specific battery operational parameters were obtained from Ambri, it is not intended to predict actual future values or precise outcomes. Instead, the results reported here should be interpreted as indicative, order-of-magnitude approximations of *potential* future value, and model results should be used more to explore how the full spectrum of value streams (wholesale revenues, retail costs, critical load resilience/independence) can help guide future analysis of installation objectives, timing, size, and pricing.

Our analysis makes it clear that the installation of Ambri storage technology at JBCC has the potential to generate substantial cost and security/reliability benefits over time. Yet it is also clear that the actual future value of Ambri batteries installed at JBCC and, by extension, the value of any storage technology installed in other locations and for other purposes, could and will vary as a function of a number of factors discussed throughout this report, including:

1. The magnitude and hourly profile of the user's electricity demand, and how this changes over hours, days, weeks and months, and how demand grows or changes over the many years of battery use;
2. The ultimate level of new renewable and traditional generation sited alongside load, and alongside battery installations, and how such generation profiles match up with the profile of electricity demand;
3. Battery operational parameters, operating modes, performance characteristics, and longevity;
4. Local utility rate levels and rate designs (i.e., volumetric or demand-based charges, or a combination of the two);
5. Wholesale market designs and prices, and the eligibility of renewable resources, Ambri batteries, or the combination of the two to participate in energy, capacity, reserve, and regulation markets;
6. The negotiation of power supply contracts and in particular whether and to what extent competitive suppliers can factor combined generation/battery net load characteristics into supply pricing;
7. Potentially significant bulk power system infrastructure changes that could lead to changes in locational marginal prices and tariff charges (such as, in this case, the potential retirement of aging generation sources in Southeast Massachusetts – Brayton Point and Canal Power Stations – and the addition of Cape Wind, as well as new investment in transmission facilities); and
8. Current and future state policies related to factors affecting the value of on-site generation and battery use, including net metering, renewable portfolio standards, grid modernization, distribution rate design, customer-facing technologies, and time-varying pricing opportunities.
9. The price of purchasing and the costs of installing batteries at the JBCC.

While these qualifications should be kept in mind, this FFS demonstrates a number of significant potential values of Ambri battery installations to JBCC, the Commonwealth, and electricity system operations in response to the key questions tested through the analysis, as described further below.

Can Ambri's LMB storage technology benefit the Commonwealth's energy and environmental policy goals?

Massachusetts has established a number of aggressive energy and environmental policies to help address the risks of climate change, foster the proliferation of advanced, low-carbon energy technologies, maintain competitive electricity pricing, encourage local economic development in the clean technology sector, and modernize the state's electric power transmission and distribution system. These include policies to support long-term contracts with wind or solar resources; renewable portfolio standards; solar generation construction and ownership by utilities; net metering; grid modernization; green jobs creation; and so on. By funding this Ambri/JBCC prototype demonstration project, the MassCEC has focused on a technology with promising technical and economic characteristics, and the potential to address many barriers to the Commonwealth's energy and environmental policies. Moreover, the project supports the state's economic and security interests by seeding the development of a local and growing advanced energy technology company, and helping the state's largest military base pursue reduced costs and greater security for mission critical operations. Electricity storage in general – and this project in particular – support all of these Massachusetts' policy interests in the following ways:

- Continued growth in renewable generation may eventually present technical challenges and amplify inefficiencies in infrastructure development and operations for the region's power grid. Such challenges may stand as technical and economic barriers – or ceilings – on how far Massachusetts and other states can go in expanding the use of low-carbon, variable renewable resources. Widespread deployment of economic storage technologies could facilitate continued growth in the integration of renewables in a number of ways. It can provide significant additional fast-start, fast-ramp resources to system operations, reduce technical and cost barriers to continued expansion, and improve the efficiency and competitiveness of the region's electricity markets.
- Massachusetts law and regulatory policy at the electric distribution level include expansion of behind the meter generation, large increases in energy efficiency programs, advanced distribution system monitoring and performance technologies, and the development and deployment of advanced metering technology at end-user locations. All of these policies are geared towards modernizing the distribution systems of Massachusetts utilities, and providing end-users the opportunity to use advanced energy technologies to take more control of electricity production, consumption and cost factors. Such outcomes could be facilitated by the widespread deployment within the state – by utilities and/or end-users – of a fast, flexible and economic electricity storage technology like the Ambri battery.
- Development of the Ambri battery (and/or other economic electricity storage technology) has large upside potential in supporting Massachusetts' efforts to support the development of an advanced energy technology sector within the state, with the expectation that as such technologies take hold they will lead to increased commercial sales of in-state and export products by Massachusetts businesses. Further, this project supports the State's security and disaster response and restoration interests by helping the state's largest military base pursue reduced costs and greater security for mission critical operations.

Considering how the development of economic storage has the potential to significantly influence the success, effectiveness, and cost of the Commonwealth's policies related to climate change risk mitigation, renewable resource development, and grid modernization, aggressive support for development of economic storage could be viewed as one of the most important research and development funding objectives for Massachusetts. The MassCEC's funding of this Ambri/JBCC prototype demonstration project thus strongly supports a consistent and comprehensive approach to advanced energy technology development, deployment and commercialization in Massachusetts.

Can installation of Ambri batteries at JBCC generate meaningful cost savings for JBCC as a retail end-use customer, and what factors affect this outcome?

Application of the RSOM analysis to the installation of Ambri batteries at JBCC demonstrates potentially significant reductions in total electricity costs to the base. See Table E2. Focusing only on JBCC electricity bills, battery use could generate savings in electricity costs over an assumed 20-year battery life of up to almost $9.5 million, or roughly 23 percent of JBCC's current retail electricity costs. This estimate is based on full-base representations of load, renewable generation, and current prices for supply and distribution rates (assuming distribution costs are collected through demand charges). It represents primarily the operation of batteries to minimize monthly peak load, and thus reduce demand charges, along with use of remaining battery capacity to capture value through price arbitrage on wholesale supply costs. Potential benefits strongly vary by assumptions with respect to combinations of load accounts, generation capacities, battery capacities, and rate structures. For example, as can be seen in Table E2, cost savings associated with battery optimization reduce to 17 percent and 12 percent at battery sizes of 8 MWh and 4 MWh, respectively. Additional results are presented throughout the Report and in Appendix B.

Table E2: Scenario Results

Total Cost and Battery Savings
Month Combined Optimization Annual Results
Delivery Price as Demand Charge

Total Costs without Battery	**Annual**	**Lifetime**
	$ 2,006,357	$ 40,127,146
Savings from Battery [1]		
4 MWh Battery	$ 245,692 12.2%	$ 4,913,846 12.2%
8 MWh Battery	$ 348,966 17.4%	$ 6,979,313 17.4%
16 MWh Battery	$ 470,451 23.4%	$ 9,409,011 23.4%

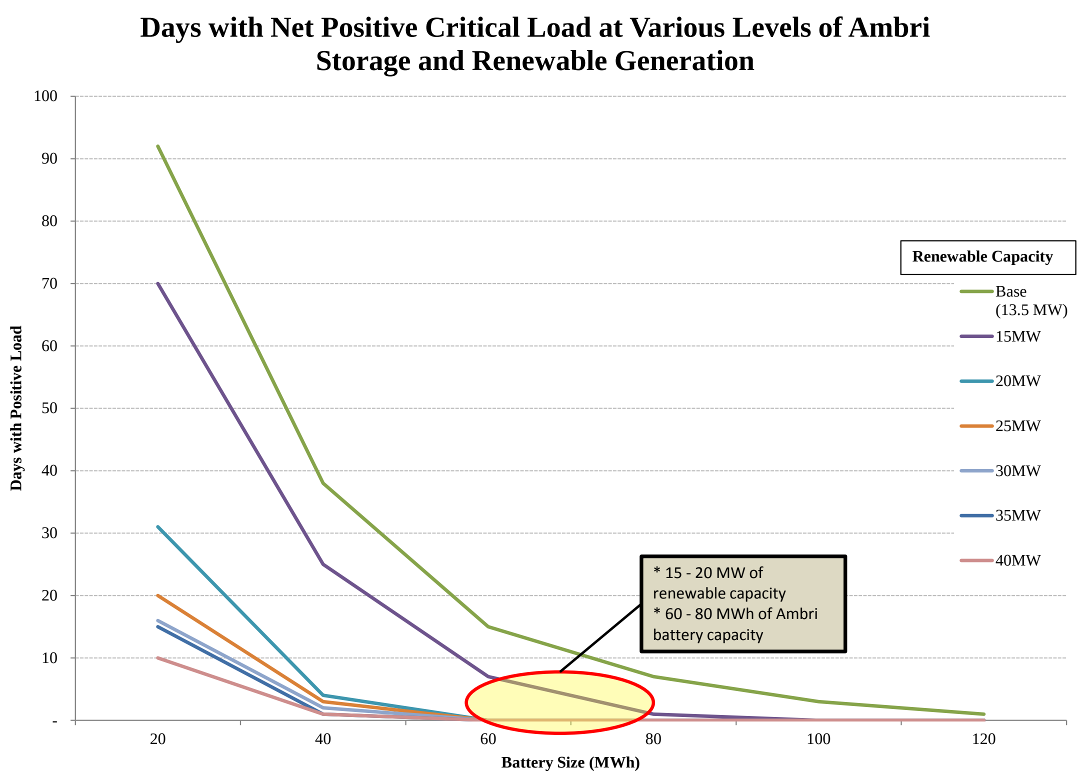
Notes:
[1] These savings amounts are calculated by subtracting the electricity costs with the battery from the baseline electricity costs without the battery.

Can Ambri's storage support more economic integration of current and/or expanded installations of renewable generation (primarily wind and solar) at JBCC (and in similar settings), and can the batteries enhance the resilience of power supply for JBCC's critical mission activities? What combinations of generation and Ambri batteries would maximize resilience of critical mission activities in the most economical fashion?

The RSOM tool was also used to assess the degree of grid independence that could be achieved through various combinations of battery storage and renewable generation. JBCC has a unique interest in energy storage, in part due to the existence of mission critical load on the base. Since storage can play a role in protecting against potential power outages, the model was used to analyze the question of how to optimally size renewable generation and battery capacity to achieve full separation from the surrounding grid – or alternatively minimize the number of hours or days when non-renewable backup generation would be needed – while still meeting the critical load on the base. JBCC provided data on the level and profile of JBCC load required for mission critical operations – that is, the level of load that cannot be interrupted, or for which there must be alternative on-site backup generation to ensure continued operations in the event of an outage on the surrounding grid. This is referred to as net critical load.

At the currently-expected level of renewable generation on the base (13.5 MW), it would take over 120 MWh (30 MW) of Ambri battery capacity to eliminate days with positive net critical load. However, RSOM was used to review how this result changes with different levels of renewable capacity on base. For this purpose, we added capacity above the Base Case level (13.5 MW) in equal increments of wind and solar PV capacity. As can be seen in Figure E2, at just an additional 1.5 MW of renewable capacity (15 MW total), 80 MWh (20 MW) of Ambri storage capacity would reduce the number of days with net positive critical load to 1; with 60 MWh (15 MW) of storage capability and 20 MW of renewable capacity, there are zero days with positive net critical load. Perhaps more importantly, even if 100% grid independence is not the objective, the analysis demonstrates that various combinations of renewable and storage capacity could dramatically reduce the capacity and amount of backup generation and fuel use needed to ensure the resilience of mission critical operations in the event of outages.

Figure E2: Critical Load Analysis Results



In effect, this analysis suggests that JBCC could approach critical load grid independence with between 15 and 20 MW of renewable capacity, combined with approximately 60 to 80 MWh (15 to 20 MW) of Ambri storage capacity. JBCC may wish to consider further analysis to determine whether this represents a "sweet spot" of combined renewable and Ambri storage capability that meets all of the military command's multiple objectives with respect to energy/emission goals, economic/cost saving mandates, and mission critical load security/independence needs.

What is the value of Ambri batteries – alone or in combination with traditional and/or renewable generating assets – in regional wholesale electricity markets?

Additional revenue generation in wholesale markets is a potentially significant value stream for battery installation at JBCC. JBCC does not currently participate as a supplier in wholesale electricity markets, and typically obtains wholesale supply through default service with the local utility and/or negotiated near-term contracts with competitive suppliers. However, our analysis strongly suggests that posturing the battery for participation in wholesale markets could generate significant additional returns (which if credited to the base's electric accounts would further reduce total energy costs). The Ambri battery has operational characteristics that could enable its users to participate in competitive wholesale markets for capacity, forward reserves, and regulation service.

Based on a battery size of 16 MWh and recent historical or expected future prices in New England's wholesale markets, participation in wholesale markets would have the potential to add up to approximately $24 million over the battery life. This is separate from (and about twice) the value from a retail cost perspective. See Table E3. It is possible that the use of the battery for participation in wholesale markets would diminish to some extent its capacity for mitigating retail costs (and vice versa), but this would depend on market rules, battery use objectives, typical battery charge/discharge cycle timing (based on load and generation), and load and generation forecasting capability. To the extent that revenue generation would be fully additive to retail cost savings, installation of 16 MWh of Ambri batteries at JBCC could generate a total reduction in base energy costs over 20 years of about $34 million. JBCC may wish to consider potential wholesale revenue benefits, and evaluate whether and how to operate the batteries to capture as much of both revenue streams as possible, and to maximize battery value based on its best and highest value in wholesale markets, retail bills, or both.

Table E3: Wholesale Market Results

Prices and Projected Payments for Ancillary Services in ISO-NE

		Projected Payments, 20 years [1]		
	$/MW - Month	**4 MWh Battery**	**8 MWh Battery**	**16 MWh Battery**
Regulation [2]	$ 16,236	$ 3,896,540	$ 7,793,080	$ 15,586,161
Capacity / Reserve Payments; New Entry [3]	$ 8,870	$ 2,128,800	$ 4,257,600	$ 8,515,200
Capacity / Reserve + Regulation Payments; New Entry [4]		**$ 6,025,340**	**$ 12,050,680**	**$ 24,101,361**

Notes:
[1] Projected annual payments assume full Battery capacity as listed is reserved for ancillary services.
[2] Based on total payments for regulation service of $11.6 million in 2012, and the average hourly regulation requirement of 59.54 MW. The average $/MW - Month was calculated by ($11.6 Million) / (59.54 MW) / (12 months).
[3] This payment represents the maximum credit a participant could receive given their participation in *both* the New England Forward Reserves and Capacity Markets in the event that new entry clears the market. The average price for Forward Reserves in the New England Wholesale markets was calculated by averaging the market clearing price in the forward reserve auctions from Summer 2013, and Winter 2013-2014. The estimated forward capacity payments given new entry by Brattle Group ("ISO-NE Offer Review Trigger Prices 2013 Study," September, 2013).
[4] At current levels (i.e. for the commitment period 2016-2017), total projected payments for participation of a 16 MWh battery in Reserve, Capacity, and Regulation Markets would amount about $8.5 million.

Can Ambri's technology enhance New England and local power system reliability and efficiency? How might emerging federal market policies or retirement of nearby power plants (e.g. Canal) affect this?

As noted above, today's power system operators rely significantly on a mix of mostly traditional fossil fuel-fired generating resources to manage the inherent variability and periodic surprises – or contingencies – of power system operations. The increase in renewable resources (in front and behind the meter) throughout the region over time could raise technical challenges with respect to reliable and efficient operation of the region's power system, by increasing the level of net load variability and associated need for potentially redundant load-following resource capability. In addition to being a challenge for operational reliability, this could over time lead to perverse outcomes where aggressive renewable and low-carbon policy mechanisms require the retention and increased operation of fast-start – but potentially aging, inefficient, and polluting – *fossil-fuel* resource capability for load-following, regulation, and reserves. Also, with growing renewable output, many of these traditional capacity resources relied on to manage load variability could have lower utilization, with financial implications for their owners.

The introduction of economic storage capability could significantly reduce such waste and redundancy in system operations over time. Indeed, to the extent significant resources retire for economic reasons, the availability of battery storage can both allow such retirements and improve the overall efficiency of power system operations. The installation Ambri batteries at JBCC may be particularly valuable in this context, since in the load region of JBCC – Southeast Massachusetts – there are at least two power plants (Brayton Point and Canal) that have often been dispatched uneconomically for reliability reasons, and that have either announced plans to retire or may do so relatively soon.[1]

[1] The New England System Operator has recently found that continued operation of the Brayton Point station is needed to maintain power system reliability. This decision may have the effect of delaying the ultimate retirement date of that facility. See Boston Business Journal, *Grid Operator Rejects Brayton Point Owner's Request to Retire the Giant Power Plant*, Morning Edition, January 2, 2014.

Changes over time in wholesale market rules could increase the value of storage assets like Ambri's battery. For example, the Federal Energy Regulatory Commission (FERC) in October 2011 required that Regional Transmission Operators (RTOs) amend their tariffs to explicitly recognize and compensate the greater contribution to meeting frequency regulation services by faster ramping resources (like Ambri's battery), and recognize the economic inefficiencies associated with meeting frequency regulation needs using slower-performing resources. The FERC Order requires RTOs to compensate regulation resources recognizing both the full capacity of regulation provided, and the quality of regulation service performance. The PJM Interconnection has already instituted such changes, and other regions are expected to follow.

Storage technologies such Ambri's – which can provide fast regulation service, efficient load following services in both directions, and can instantaneously change directions back and forth between charge and discharge states – could thus help meet a number of goals with respect to power system reliability and dispatch efficiency. Perhaps more importantly, batteries offer a responsive technology that is particularly well suited to helping maintain reliability in the face of the increasing net load variability that comes with integration of a greater level of renewable resource generation, and does so without requiring an increase in generation by resources that emit significant quantities of carbon dioxide and other pollutants.

2. INTRODUCTION

Overview

Economic energy storage has the potential to fundamentally change the economics, operational reliability, fuel supply, and environmental impact of the electric sector, and the emergence of a successful electricity storage industry in Massachusetts would generate substantial jobs and economic benefits for years to come. This study represents an initial operational and economic assessment for an emerging Massachusetts-based storage company – Ambri Inc. – that is developing a battery with the potential to have such a transformative impact on the industry. This assessment – a Functional Feasibility Study funded in part through the Massachusetts Clean Energy Center's InnovateMass Program – evaluates the value of installing Ambri batteries at Joint Base Cape Cod, one of the state's largest consumers of electricity and generators of customer-owned renewable resources.

The MassCEC's InnovateMass Program is a competitive program that provides grants to projects that offer innovative and effective clean energy solutions – in particular, those with the strongest potential to help address the Commonwealth's energy and environmental challenges. Funding is provided for teams that can prove out new technologies, or combine existing technologies in clean energy demonstration projects that are scalable, have strong commercialization potential, create jobs, and help reduce energy use and associated environmental impacts.[2]

In May of 2013, the MassCEC selected Project Vigilance – including this initial FFS – for funding under the InnovateMass Program. The goal of Project Vigilance is to demonstrate the LMB storage solution under development by Cambridge-based Ambri at JBCC, which is a unique end-use location for storage demonstration since it combines high electricity demand, significant variable renewable resource development, and mission-critical functions requiring high quality and security of supply. Project Vigilance was selected by InnovateMass as a project that could meet numerous state advanced technology demonstration and energy/environmental policy objectives. Specifically, as noted in the Project Vigilance proposal to the InnovateMass Program, the project will help:[3]

- Achieve the InnovateMass Program goal to identify solutions to some of the energy challenges in the Commonwealth of Massachusetts and beyond including the development of economic energy storage technologies to optimize the variable renewable energy system efficiency and effectiveness to reduce fossil fuel backup generation, improve power quality or improve grid reliability;
- Accelerate the demonstration of Ambri's storage technology, pave the way for commercialization, and thereby continue to generate high-quality jobs in Massachusetts;
- Continue the leadership role the Commonwealth of Massachusetts has played in advanced energy technology innovation, development and commercialization;

[2] See MassCEC's InnovateMass program website at http://www.masscec.com/programs/innovatemass.
[3] Ambri, Inc., *Proposal to the Massachusetts Clean Energy Center InnovateMass RFP*, January 18, 2013.

- Provide an example for Department of Defense (DoD) bases around the world as well as a wide range of other types of wholesale and retail customers for electricity storage; and
- Accommodate and value the full potential of renewables integrated into the grid and in end-use operations, by maximizing the potential of renewable resources to increase end-user and power system reliability, and reduce electricity costs.

Project Vigilance is a unique partnership between several Massachusetts-based energy, finance, and defense industry corporate and military entities, including Ambri, MDFA, Analysis Group, Raytheon, and Joint Base Cape Cod. Through this grant, Ambri will work towards the deployment of large scale energy storage at JBCC to meet a number of key defense and energy industry goals, including reliable integration of variable renewable resources, cost control, and energy security and independence for critical mission operations. JBCC is a unique location for such a demonstration project – it is a joint-use base, home to multiple military commands and government agencies including Otis Air National Guard Base, Camp Edwards, Cape Cod Air Force Station and the United States Coast Guard’s Air Station Cape Cod. Activities at JBCC include key operations that require a high degree of power security and quality. In addition, JBCC is one of the largest electricity users in the Commonwealth with annual electricity consumption of approximately 44 gigawatt-hours (GWh), and has one of the largest and growing end-user portfolios of variable renewable generation (wind and solar) in all of New England.

Project Vigilance was designed to help InnovateMass meet numerous goals, including helping advanced energy technologies move closer to commercialization and establishing manufacturing operations, creating jobs in the Commonwealth and generating associated economic activity; accelerating the growth of technologies to support expansion of clean energy options to reliably meet Massachusetts’ consumers power needs while meeting key State energy and environmental policy objectives; and enhancing the Commonwealth’s presence in the growing clean energy technology sector.

Project Elements and Purpose of the FFS

Project Vigilance storage demonstration will proceed in two phases, ultimately resulting in significant deployment of Ambri LMB storage systems. Deployment will be initially at JBCC, and possibly at other site(s) to be facilitated by MDFA. Phase I – which is funded in part by the MassCEC InnovateMass Program – includes this FFS plus the initial prototype deployment at JBCC.

The conclusions of FFS will be used to determine how best to deploy a full-scale Ambri LMB system at JBCC, considering key factors such as the best size and use of the Ambri battery given its operating capabilities. The second part of Phase 1 is the deployment of Ambri’s LMB prototype of 25 kilowatt-hour (kWh)/6 kilowatt (kW), which will begin in 2014. The prototype will be smaller than full-scale deployment, but will be designed to meet and demonstrate all of the required operational parameters of the commercial Ambri LMB system. It will likely be installed at JBCC in the location of the full-scale deployment, and its operations will simulate how the larger system will function. Phase 2 will be completed upon success of Phase 1, and will involve the deployment of a commercial Ambri LMB system. The ultimate size of the commercial-scale system will be determined based in part on this FFS and the prototype demonstration in Phase I.

The FFS responds to both the objectives of the MassCEC's InnovateMass program and the demonstration and commercialization objectives of JBCC and Ambri. Thus the Study investigates the reliability, security and energy/environmental policy value of Ambri's storage technology, and the economic value of various levels of storage installation on site at JBCC. As described in the Executive Summary, the analysis is designed to test a number of technical questions about how the application of this battery storage system could serve a number of functions for JBCC. Moreover, the study was structured to answer questions about the value of Ambri's storage technology in two contexts: First, what is the value in military applications using actual data related to specific electricity generation consumption, and mission critical activities at the Commonwealth's largest military base, JBCC? Second, what is the broader reliability and economic value of Ambri's storage technology in the wholesale market context, and considering the energy and environmental policies and goals of the Commonwealth?

This report documents the analytic approach and results, including answers to all of the questions outlined in the Executive Summary. Some of the questions are answered qualitatively with an understanding of how Ambri's battery technology could and likely would operate upon full commercialization. Other questions are answered specifically and quantitatively through the application of Analysis Group's RSOM tool, a constrained optimization model designed to evaluate the economic impact of energy storage technologies under a wide range of potential combinations of electrical load, generation resources, and wholesale/retail cost drivers.

Section 3 provides background on the study context – including (i) the technical capabilities and operating parameters of the Ambri LMB storage technology; and (ii) a summary of JBCC's missions, operations, electrical load profile, and the operating characteristics and generation profile of renewable power assets currently operating or soon to be installed on the base. Section 4 presents findings and observations including a general discussion of potential benefits associated with integration of storage technology in power systems or retail locations, and Section 5 provides quantitative results from using RSOM to assess the specific circumstances of operating Ambri storage technology at JBCC. Finally, Appendices provide additional detail on analytic method and results.

3. CONTEXT: JBCC LOAD AND GENERATION PROFILES, AND AMBRI'S BATTERY STORAGE TECHNOLOGY

Joint Base Cape Cod

Figure 1: Map of JBCC

The Joint Base Cape Cod is a full scale, joint-use military installation spanning over 20,000 acres at the western end of Cape Cod, Massachusetts. JBCC has been in military use since 1911, and is currently home to five military commands, including the Massachusetts Army National Guard at Camp Edwards; the Massachusetts Air National Guard at Otis Air National Guard Base; the 253rd Combat Communications Group, also at Otis Air National Guard Base; the 6th Space Warning Squadron phased array radar site at Cape Cod Air Force Station; and the U.S. Coast Guard at Air Station Cape Cod.

The military commands at JBCC work to protect the land, sea, and air of the northeastern United States, and many military units and service members who work and train at the JBCC are participating in missions around the world. In addition to the military commands, numerous related military divisions, other federal and state agencies, municipalities, and civilian organizations use the base.[4]

JBCC is one of the largest single users of electricity in Massachusetts. Various parts of the base are either fed directly from feeders with the local distribution utility (Northeast Utilities), or are on subfeeders of a grid and substation owned and operated by the Air Force 102d Intelligence Wing (the "Base Grid"). Annually, including all load associated with JBCC operations, the base consumes on the order of 40 gigawatt-hours (GWh) of electricity, with a peak load of over 6 megawatts (MW). In addition, JBCC operates significant traditional and renewable generation on base.

Figure 2: Monthly Load Profile

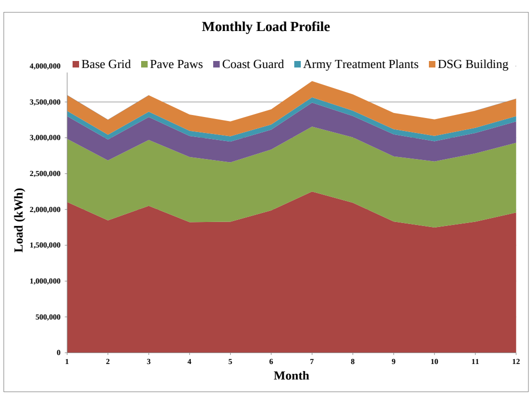
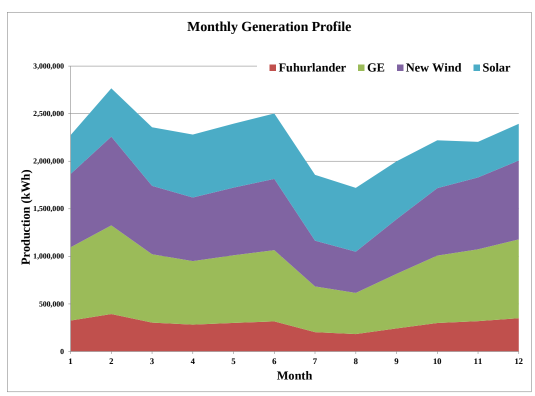


Figure 3: Monthly Generation Profile



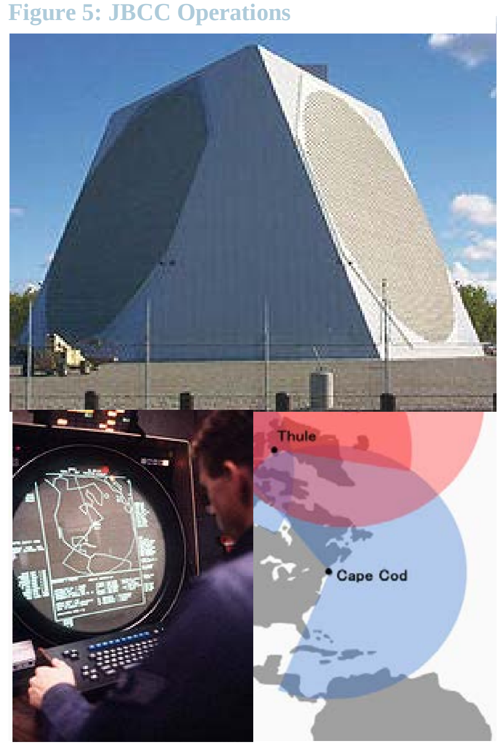
[4] For more information on JBCC, see the base's website at http://states.ng.mil/sites/MA/JBCC/index.html.

Figure 4: JBCC Turbines

In addition to over ten generators backing up critical load operations, JBCC has installed 7.5 MW of wind generation, and is in the process of procuring the installation of on the order of 6 MW of solar PV on site.

JBCC is located in the lower Southeast Massachusetts (SEMA) load zone, a region that is at the southeast corner of New England's power grid, and has been subject to relatively frequent power disruptions, particularly when facing ocean-based storm systems. The reliability of this part of the region's power system could be further weakened if retirement proceeds for economically-challenged generating capacity at the two largest power plants in the SEMA region – Canal and the Brayton Point Station, which together represent approximately 2,600 MW, or over 40 percent of SEMA generating capacity.[5] Prevailing and potential future power system conditions heighten the value to JBCC of building greater on-base resilience to interruptions in power supply. In addition, with back-up power supply and extensive support capability on site, JBCC has and can operate as a safe haven for the community and a base for large scale recovery efforts (such as power restoration efforts following major storms).

Figure 5: JBCC Operations



Considering the unique size, electrical load, generation, critical mission, and disaster recovery functions, JBCC – like many other military installations across the country – is an ideal location for the integration of an energy storage technology that has the unique operational flexibility of the Ambri LMB storage system (described in more detail in the next section). This is because JBCC is not only a very large user of electricity, it has a substantial and growing quantity of highly variable renewable generating resources on-site leading to highly-variable net load, and has critical mission functions that require a great deal of power system resilience, quality, and independence. Battery storage can thus help JBCC lower operational costs, improve the economics and functionality of on-site generation, and improve the hardening of base operations against power system outages occurring at the local distribution company or regional power system levels.

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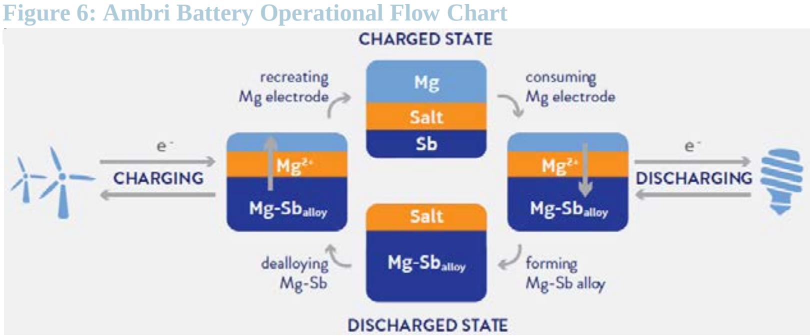
[5] Brayton Point has filed a non-price retirement request with the region's power system operator, ISO New England. See Mariah Winkler, ISO-NE, *2017-2018 Capacity Commitment Period Evaluation of Non-Price Retirements*, presentation to NEPOOL Reliability Committee, December 19, 2013. It is widely expected that prevailing market economics could also lead to the retirement of the Canal power plant.

Ambri's Liquid Metal Battery

Founded in 2010, Ambri Inc. (formerly known as Liquid Metal Battery Corporation) is based in Cambridge, Massachusetts, with manufacturing operations located in Westborough, Massachusetts. Ambri's technology is a liquid metal battery originally designed in the lab of Dr. Donald Sadoway, a professor at the Massachusetts Institute of Technology, based on the chemistry used in extreme electrochemical processes, ranging from aluminum smelting, to molten oxide electrolysis for extracting oxygen from lunar regolith, to lithium polymer batteries. The battery research was supported by the Deshpande Center, the Chesonis Family Foundation, ARPA-E and the French energy company, Total. In 2013 Ambri was recognized as a winner of the Global Cleantech 100 and awarded as the "Rising Star of the Year," and was named a TR50 winner — one of 50 Disruptive Companies of 2013 – by the MIT Technology Review. Ambri has received Series B financing from Khosla Ventures, Total, and Bill Gates.[6]

Figure 6: Ambri Battery Operational Flow Chart



The Ambri battery is an all-liquid design with three components – a salt (electrolyte) and two distinct metal layers (electrodes; pictured in Figure 6 as Magnesium and Antimony for purposes of illustration only, as Ambri is commercializing a proprietary, lower-cost, higher-voltage chemistry that operates at a lower temperature). Battery electrode materials are selected for high voltage capability and low cost. Cells operate at elevated temperature and, upon melting, the three layers self-segregate and float on top one another due to their different densities and levels of immiscibility. 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 one electrode, delivering power to the external load, with the electrons returning back into the other electrode. Internally, in this discharge mode, this causes ions to pass through the salt creating an alloy. In charging mode, power from an external source (e.g., a generating source such as a wind turbine or PV array on location) pushes electrons in the opposite direction, returning the system to three distinct liquid layers.

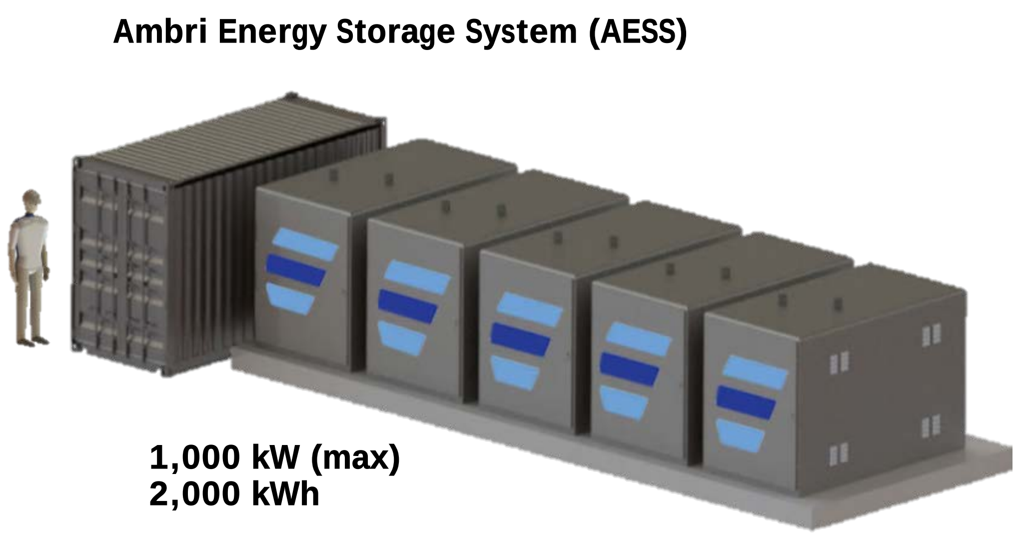
There are a number of advantages of Ambri's technology – compared to many other energy storage devices – from the perspectives of flexibility, economics, power system operation and reliability, and safety. The battery cell is simple, uses earth-abundant materials, and the all liquid design avoids the main failure mechanisms experienced by solid components in other battery technologies. Ambri's technology is also unique in its ability to serve as both a power and an energy resource for the electric grid. A power resource can quickly switch from charging to discharging, and typically needs to provide power for relatively short periods of time (e.g., from seconds to ~15 minute intervals), and in

[6] For more information on Ambri, see their website at www.ambri.com.

contrast, an energy resource will usually dispatch power over longer periods (e.g., hours). Applications that require a high power battery include ancillary services like frequency regulation and voltage support, and applications that require a high energy capacity include energy arbitrage, peak shifting, and renewable integration. While high power batteries (such as Li-ion batteries for grid applications) can technically operate at much lower power ratings and therefore discharge over multiple hours, the high cost per unit of energy storage capacity makes these batteries uneconomical for multiple-hour / energy resource applications. Ambri will commercialize modular battery systems with 2 MWh of energy storage capacity. These systems are designed for optimal performance with a power output of 400 kW for 5 hours at a price that will enable use for both power and energy applications. The same Ambri battery will be able to discharge at a power of 1 MW for up to two continuous hours, or provide any level of required power between -1 MW and +1 MW.

The unique properties of the Ambri battery allow it to qualify as a fast responding resource to meet power system reserve, load following, and frequency regulation needs, and enable it to efficiently and effectively balance the variability of renewable resources. A single Ambri battery cell is small, but cells may be aggregated with little or no loss of efficiency so that installations may be sized to optimally meet reliability or economic objectives in both wholesale and retail market settings. Finally, 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 7: Ambri Storage



Overview of Analysis

There are a number of ways in which Ambri's flexible storage technology may be used in the context of power system operations, wholesale electricity markets, and end-user applications. How the battery is used depends on a number of factors related to power system and market pricing conditions, market participant or end-user needs and interests, and ultimately the relative economics of battery operating options. And as these interests and opportunities may change in importance or value over time, the mode of operation for the Ambri battery may also be adjusted to meet highest-value needs of users as they change.

Examples of battery value could include at least the following:

- An end-user with behind the meter generation – like JBCC – can use batteries to optimize the value of the generation and/or minimize the net cost of electric service; and
- In the case of a municipality or large user with significant power quality, disaster service/restoration, or critical mission needs, batteries can be used to provide added resilience to services and operations and/or minimize the need for and use of back-up diesel or other generation.
- In the power system context, a regional transmission or distribution system operator could use the battery to improve the speed of regulation and load-following services, or possibly to defer the need for investment in additional transmission or distribution system infrastructure at weak parts of the system.
- The existence of competitive wholesale markets enables market participants to use Ambri batteries as stand-alone assets in capacity, energy, reserves, and regulation markets, or to combine storage with generation assets in a way that increases or maximizes the value of those assets through firming up accredited capacity levels and/or through arbitrage across temporal variations in energy market prices.

The scope and method of analysis in this study were selected to explore potential value streams across many such potential uses. The RSOM 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, RSOM analysis uses the specific geographic focus, wholesale/retail market structure, load levels, and generating capacity associated with installation of batteries at JBCC. The specific areas of potential benefits reviewed in this study qualitatively or modeled and quantified using RSOM are presented in Table 1.

Table 1: Potential Battery Benefits and Model Approaches

Battery Value	Perspective	Description	Model Approach
Retail Costs	End-use customer	Battery used to minimize all-in cost of electricity	Apply constrained optimization on battery use to minimize customer monthly bills
Critical Load; Resilience & Independence	End-use customer	Battery used to protect critical end-use operations against transmission or distribution outages, or minimize use of back-up generation	Iterative application of battery optimization to minimize hours with net positive critical load
Energy Market Arbitrage	End-use customer or wholesale market participant	Available battery storage capability used to maximize the daily/weekly value of generation in energy market	Apply constrained optimization on battery use to maximize energy market revenues (and/or minimize wholesale energy costs) considering base generation resources and load
Capacity Market Revenues	End-use customer or wholesale market participant	Battery used in power/capacity mode to gain revenues in capacity market	Calculate annual capacity market revenues under different market forecasts
Reserve Market Revenues	End-use customer or wholesale market participant	Battery used in power/capacity mode to gain revenues in reserve market	Calculate annual reserve market revenues based on historical reserve market prices
Regulation Market Revenues	End-use customer or wholesale market participant	Battery capability offered as a regulation resource	Calculate annual regulation market revenues based on average historical market prices
Deferral of Infrastructure Investment	Transmission or distribution utility	Strategic placement of battery storage to support local system reliability	Discuss qualitatively
Power System Reliability and Efficiency	Regional power system operator, wholesale customers	Integration of storage to improve the reliability and efficiency of managing power system peak loads, load-following, and reserve requirements	Discuss qualitatively
Integration of Renewable Resources	Public Policy	Facilitate greater use of low/zero carbon resources to meet state or federal policy objectives; reduce need for traditional peaking resources to balance variability	Iterative application of battery optimization to reduced use of backup generation at increasing levels of renewable integration; discuss qualitatively

Estimates of battery value are developed across all potential modes of operation – from using batteries to reduce monthly all-in electricity costs by modifying demand and/or volumetric rates; to including partial or full use of the batteries to capture revenues from the wholesale market; to constructing battery and renewable power sources on-site to harden base critical mission operations against potential interruptions in power supply from the power grid, or to achieve full grid independence. Since the magnitude of any/all of these battery values depend on both JBCC system (generation and load) characteristics and the size and operating mode of the Ambri battery, the analysis is conducted across a range of potential resource, load and battery combinations. Specifically, model results are generated with variations in the following key inputs:

- **JBCC load:** As noted, JBCC's load is spread across a number of accounts. For the purpose of our base case analysis we aggregate all accounts to represent the base as a single, large account. It is also possible to run the analysis including only a subset of individual accounts.

With respect to the critical load scenario (discussed in more detail in the next section), we include only that load on the base deemed necessary for mission critical operations.

- **JBCC generation:** JBCC generation sources modeled include (a) the Fuhrlander wind turbine (1.5 MW) in the south part of the base, (b) the 4 existing GE wind turbines (1.5 MW each) in the north part of the base, and (c) a solar PV project (6 MW) planned for near-term installation and operation in the south part of the base. Similar to load, for the purpose of our base case analysis we aggregate all generation to represent the base as a single account with generation. It is also possible to run the analysis including only subsets of generation assets. Further, one of the critical load analysis scenarios reviews the degree of independence achievable with increased levels of renewable capacity relative to current plans.
- **Ambri battery size:** For the purpose of our base case analysis, we model three different levels of battery capacity installation at JBCC: 4, 8, and 16 MWh of battery energy storage (or 1, 2, and 4 MW of peak power output, respectively). However, it is also possible to run the analysis at any battery size. For example, with respect to the critical load analysis, we run multiple levels of battery capacity to test how battery size influences the ability to meet critical loads relying only on generation on-site. (It should be noted that while our analyses assume a set of *optimal* (e.g., highest roundtrip efficiency) and fixed charge, discharge, and efficiency parameters for Ambri batteries, in reality the batteries are more flexible. For example, whereas our analysis assumes that an 8MWh battery can discharge no more than 2MW per hour for four hours, this Ambri battery could actually discharge up 4MW per hour, although for a shorter period of time, and with a reduced level of efficiency).

4. AMBRI BATTERY STORAGE – RELIABILITY, EFFICIENCY AND POLICY BENEFITS

Overview of Storage Benefits

Power systems must balance load and generation on a near-instantaneous basis, while ensuring there exist sufficient resources capable of meeting this need every minute of the year, and across wide variations in demand for electricity. In addition to demand-response resources, this requires the construction and operation of a significant amount of redundant or underutilized generation and transmission infrastructure, and potentially limits the integration of generating resources with variable, uncertain, or unpredictable power output (such as solar PV and wind resources). It also can require the retention or construction of less efficient thermal energy generating resources (such as oil- and natural gas-fired turbines), and the operation of resources outside their most efficient operating range, to ensure sufficient fast response capability for managing variations in system load.

In addition, customers' ability to manage their own energy costs (as a function of time-varying prices at the wholesale and distribution levels, or to optimize the value of behind the meter generation) is limited by the inability to manage or direct the flow of power to and from the grid based on usage timing and/or variable generation output.

The development and widespread installation of economic electricity storage capable of flexible mode operation and instantaneous charge or discharge – such as Ambri's LMB technology – could change existing electric grid operational limitations, expand customer cost management and asset utilization, and could transform the power system as we know it. It would generate efficiency, cost, health, and environmental benefits across all levels of the value chain – from system operations and reliability, to utility infrastructure development, to wholesale market resource acquisition and dispatch, to renewables development and climate change risk management, to end-user power quality and independence.

Storage is not new. The value of large-scale storage can be seen in power system reliance on pumped storage hydro resources for system balancing, load following, reserve operations, and energy price arbitrage. And other storage technologies have been developed and demonstrated in small-scale applications throughout the country. However, additional hydro pumped storage capability is severely limited by land use and siting limitations, and to-date new electricity storage technology development has not landed on a technology with sufficient scale, operational flexibility, reliability, and economic competitiveness to alter the landscape.

Which storage technology is best suited to help power system reliability, customer costs, and energy or environmental policy outcomes is dictated by a number of factors tied to storage technology characteristics, factors unrelated to the technology, and the perspective of the entity using it. Key value factors in the development of storage technologies include the following:

- What are the design and operating characteristics of the battery – e.g., what are the storage and power output limitations? How quickly can the technology switch from charge to discharge, and what are the limits on charge/discharge rates? What is the efficiency penalty in the charge-to-discharge cycle?

- What is the cost of the technology? How likely are costs to drop with increasing production? What are the materials needed and how are they obtained? Are there likely siting or permitting challenges? What might the health, safety and environmental impacts be if there were wide scale adoption of the storage technology?
- Is the technology to be sited behind the meter or as a wholesale resource (or both)? If the former, what is the rate structure of the end-user's tariff (i.e., demand-based versus volumetric-based tariffs); are there net metering provisions that should be considered?
- Does the customer have power quality and/or grid separation needs or aspirations? Can the characteristics of the battery technology be used alone or in combination with on-site or back up generation to increase the resilience of end-use needs to potential power outages?
- Is the goal/value to pair the storage technology with a variable resource? If so, what is the quantity and type of resources with which the storage is paired? How variable are the generating resources, and what does that imply about optimal use value?
- If used in a wholesale context, with or without paired generation, what are the potential revenue streams? What markets (e.g., energy, capacity, regulation, reserves) would the storage technology be eligible for under current rules? How much value is in those markets in the region of interest? Are there forthcoming changes in wholesale market eligibility and pricing? In what ways would pairing storage with variable generation resources – or to support participation in demand response programs – increase value in wholesale markets?
- What factors and limitations affect investment in transmission and distribution infrastructure in the region in question, and could the storage technology lead to avoidance or deferral of such investments?

The answers to these questions, and perspectives on storage value, will likely vary significantly across storage technologies, over time, across regions, across customers, and across industry/regulatory structures. It is against this backdrop that the MassCEC has funded this demonstration battery storage project to assess the value and feasibility of the Ambri storage technology, provide for the deployment of prototype installations at JBCC, and accelerate the development and commercialization of this potentially transformative technology.

The quantitative assessment in this report is based on specific circumstances related to the JBCC prototype installation context – i.e., JBCC's load, generation, and market characteristics. However, where possible the report also explores qualitatively and quantitatively how battery value is affected by varying some of the key factors identified above, such as rate structures, load/generation quantity and characteristics, user objectives, and market opportunities. In addition, the assessment includes a more general review of the potential benefits of Ambri's technology would be from reliability and policy perspectives. This section first summarizes qualitatively potential reliability and policy benefits, and then specifically presents model results quantifying cost/revenue benefits associated with optimized operation of Ambri battery technology at JBCC.

Power System Reliability and Dispatch Efficiency

Today's power system operators rely on a mix of mostly traditional fossil fuel-fired generating resources (in addition to some pumped storage and other capability) to manage the inherent variability and periodic surprises – or contingencies – of power system operations. There are two aspects of this that introduce inefficiencies in power system operations. First, aging and/or inefficient fast-start, flexible operation fossil-fired resources – such as older oil- and natural gas-fired boilers and combustion turbines – are retained (and paid for in capacity and reserve markets) beyond the point of economic retirement. Second, on a day-to-day basis system operators will often dispatch on-line generating units off of their most efficient operating level to manage load and generation variability, and/or to have sufficient spinning reserve available to follow swings in load or respond to sudden system contingencies.[7] Historically, this has occurred with little or no attention to how effective a resource may be in providing such regulation/load following service – i.e., how quickly and accurately does a resource respond to system operator requests to change output levels? While markets are generally designed to take such actions in the most efficient manner possible given system conditions and available power system assets, the introduction of economic storage capability – combined with market rule changes to recognize the quality of asset response – could significantly reduce such waste and redundancy in system operations over time.

These circumstances can be amplified by the integration of an aggressive level of renewable resources. As Massachusetts and other states institute policy mechanisms to address the risks of climate change and advance the development of emerging low-carbon power resources (primarily wind and solar PV), the level of *net load variability* and associated need for fast start, fast ramping resources increases.[8] This can lead to perverse outcomes where aggressive renewable and low-carbon policy mechanisms require an increase in requirements for fast-start fossil-fuel resource capability, and lead to an increase in the inefficiencies associated with retaining existing fossil-fuel resources (and/or attracting new ones), to manage system needs for load-following, regulation, and reserves.

In effect, absent fast-response, low-emitting resources (such as the Ambri storage technology), the increase in renewable resources could lead to an increased reliance on relatively inefficient fossil-fired resources (along with associated emissions of CO_2 and other pollutants) to manage greater net load variability.

Part of the solution to this challenge is to ensure that market signals reward resources with superior response characteristics. There are significant differences in the efficiency with which various resource types can meet ancillary service needs. For example, the FERC has recognized that while it

[7] System operators administer markets in various "ancillary services," and/or follow specific operating procedures as needed – either along with or in place of market-based mechanisms – to maintain federally-enforceable system reliability standards. Such ancillary services include spinning and non-spinning reserves (resources prepared to come on line if/as needed to address sudden system changes), load following services (ramping, automatic generation control and regulation capability to following changes in net load on timeframes of seconds to minutes to hours), and black start capability (the ability to come on line to help re-energize the system after an outage).

[8] "Net load variability" represents the actual variability that needs to be managed by power system operators, including both variability in load over time – which is somewhat predictable, particularly over shorter time periods – and changes in renewable generating resource output – which is far less predictable and can include sudden, significant swings. The most challenging circumstances arise when a period of rapid change in load is coincident with rapid or sudden changes in variable generation output (e.g., a period when load is rapidly increasing at a time when wind or solar output is rapidly decreasing).

may be possible to use a large combined cycle or combustion turbine generator to meet regulation and other load following needs, they can not do so as quickly or efficiently as some emerging storage technologies. In October 2011 FERC required that RTOs amend their tariffs to explicitly recognize and compensate the greater contribution to meeting frequency regulation services by faster ramping resources, and recognize the economic inefficiencies associated with meeting frequency regulation needs using slower-performing resources. The FERC Order requires RTOs to compensate regulation resources recognizing both the full capacity of regulation provided, and the quality of regulation service performance.[9] An example of this (from PJM) is described in the Executive Summary. To the extent a similar performance measure is incorporated in New England dispatch and compensation over time, the value of Ambri's fast-response storage installation at JBCC – or elsewhere in the state or region – would increase.

An increase in storage capability could reduce the total amount of generating resources needed to meet needs during peak hours (in the summer, in New England). To the extent that storage can help by fully charging in off-peak hours (when load and prices are lower) in order to be available as a discharge resource during peak hours (when load and prices are higher), the overall need for generating capability is reduced, the load factor for a region increases (to the extent storage capability is behind the meter and thus measured as load or facilitating demand response), and the overall utilization of the fleet of generating assets improves.[10]

Storage technologies such as Ambri's could thus help meet a number of goals with respect to power system reliability and dispatch efficiency. They can help RTOs meet reliability obligations and in doing so displace inefficient RTO dispatch practices. They may allow for the economic retirement of some aging resources. Perhaps more importantly, batteries offer a responsive technology that is particularly well suited to helping maintain reliability in the face of the increasing net load variability, doing so without increase carbon emissions from generation otherwise needed to integrate renewables.

The Public Policy Perspective

With the passage of the Green Communities Act in 2008 and subsequent regulatory actions, Massachusetts has established a number of aggressive energy and environmental policies to help address the risks of climate change, foster the proliferation of advanced, low-carbon energy technologies, and modernize the state's electric power transmission and distribution system. Most of the other states in the Northeast are similarly focused on the development of an advanced energy economy, secure and flexible grid, and evolution of our power supply away from carbon-intensive generation resources towards renewable and other low-carbon approaches to meeting electricity needs. The proliferation of such policies and the continued decrease in underlying costs of wind and

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[9] Federal Energy Regulatory Commission, *Frequency Regulation Compensation in the Organized Wholesale Power Markets*, Order Number 755, Docket Numbers RM11-7-000 and AD10-11-000, October 21 2011 (hereafter "Order 755"), page 2.

[10] Load Factor is a measure of how average hourly consumption compares to hourly consumption at the time of system peak. For example, if average load in a given year is 15,000 MW, and summer peak load is 30,000 MW, the load factor for the region is 50 percent. By decreasing the resources needed to meet demand during the limited number of peak hours in the year through additional storage capability, the system requires fewer MW of generating capability to be available year-round to meet demand during peak hours.

solar technologies has led to significant increases in the construction of variable power supplies across New England, at the bulk power system level and behind the meter.

The development and commercialization of economic storage technology could facilitate continued growth in the integration of renewables, by helping address a number of potential technical, economic, and cost barriers to continued expansion. By funding this Ambri/JBCC prototype demonstration project, the MassCEC has focused on a technology with promising technical and economic characteristics, and the potential to address many barriers to the Commonwealth's energy and environmental policies. Moreover, the project supports the state's economic and security interests by seeding the development of a local and growing advanced energy technology company, and helping the state's largest military base pursue reduced costs and greater security for mission critical operations.

Specifically, electricity storage in general and this project in particular support Massachusetts' policy interests in a number of critical ways. As noted above, continued growth in renewable generation would eventually present technical challenges for the operation of the region's power grid, on which all Massachusetts residents and businesses depend for reliable electricity supply. This reliability challenge stands as a technical barrier – or ceiling – on how far Massachusetts and other states can go in expanding the use of low-carbon, variable renewable resources, without creating difficult power system operational challenges.

Similarly, continued growth in variable renewable generation could also amplify inefficiencies in power grid infrastructure development and operations. Massachusetts residents and businesses also rely on smooth operation of the region's competitive wholesale electricity markets for efficient and competitively-priced power supplies. This economic/efficiency issue represents something of a cost challenge to continued aggressive investment in low-carbon, renewable resources. Widespread deployment of economic storage technologies could provide significant additional load-following capability to efficiently and effectively manage variations in net load without adding or operating redundant or excess fossil-fired generation capacity for this purpose.

The policies that could over time be affected by such technical or cost ceilings/barriers include policies to support long-term contracts with wind or solar resources; renewable portfolio standards; solar generation construction and ownership by utilities; and net metering. While implementation of these policies in Massachusetts and other states to-date is generally manageable from a system operational perspective, continued growth in all of these areas will continue to increase power system net load variability. All of these policies support the Commonwealth's goals to address climate change (through these policies and the standards set forth in the Global Warming Solutions Act), and support development of renewable resources. Widespread deployment of economic storage technologies could provide significant additional fast-start, fast-ramp resources to help respond to sudden swings in renewable capacity output.

Massachusetts has also invested much effort in supporting the development of an advanced energy technology sector within the state, with the expectation that as such technologies take hold they will lead to increased commercial sales of in-state and export products by Massachusetts businesses. Doing so will generate in-state economic growth and support ongoing growth in quality "clean-tech" jobs within the state. Development of the Ambri battery (and/or other economic electricity storage technology) has large upside potential in this area, both as a potential major clean-tech manufacturing growth sector, and as an enabler for growth in development, construction, and installation of the various renewable generation industries it supports.

Massachusetts has also focused policy efforts at the electric distribution level and on the tools utilities and end-users need to have to avoid costly infrastructure investments, reduce outages, and minimize costs. Policies focused on the tools and opportunities residents and businesses have include the expansion of behind the meter generation, large increases in energy efficiency programs, advanced distribution system monitoring and performance technologies, and the development and deployment of advanced metering technology at end-user locations. All of these policies are geared towards modernizing the distribution systems of Massachusetts utilities, and providing end-users the opportunity to use advanced energy technologies to take more control of electricity production, consumption and cost factors.

Finally, the Massachusetts Department of Public Utilities (DPU) has been proactive in supporting such efforts through policy and rate designs that support end-user generation options, provide technology and incentives for consumers to adjust consumption based on hourly pricing (including "customer-facing" technologies and time-varying rates), and for companies to "optimize load" and better manage distribution system operations and efficiency (through "grid-facing" technologies, cost recovery incentives, and regulatory requirements).[11] The policy focus, requirements, and opportunities in the DPU's Grid Mod Order are strongly focused on the need to enable behind the meter generation, end-user arbitrage of energy prices, distribution company load optimization, and reliability. Every one of these objectives and policies could be facilitated by the widespread deployment within the state – by utilities and/or end-users – of a fast, flexible and economic electricity storage technology like the Ambri battery.

Considering how the development of economic storage has the potential to significantly influence the success, effectiveness, and cost of the Commonwealth's policies related to climate change risk mitigation, renewable resource development, and grid modernization, aggressive support for development of economic storage could be viewed as one of the most important research and development funding objectives for Massachusetts. The MassCEC's funding of this Ambri/JBCC prototype demonstration project thus strongly supports a consistent and comprehensive approach to advanced energy technology development, deployment and commercialization in Massachusetts.

[11] See Massachusetts Department of Public Utilities, *Investigation by the Department of Public Utilities on its own Motion into Modernization of the Electric Grid*, DPU 12-76-A (hereafter "Grid Mod Order"), pages 1-4.

5. RSOM MODEL ANALYSIS: ASSESSMENT OF AMBRI BATTERY OPTIMIZATION AT JBCC

Overview

Our study relied upon the application of Analysis Group's Renewables/Storage Optimization model to estimate the value of Ambri battery installation at JBCC. Before describing the results of the analysis here, the RSOM is summarized here and described in greater detail in Appendix A. The following section contains results for the base case analysis (additional scenario results are presented in Appendix B). Finally, while our analysis is particular to Ambri batteries and installation at JBCC, we describe how the method and, to some extent, the results, are transferrable to other military applications, other locations, other market structures and pricing contexts, and for different battery technology characteristics.

Because the value of electricity storage to wholesale market participants or retail customers (with or without on-site generation) depends on a number of case- and site-specific factors, our analysis of Ambri battery value is configured using specific details on historical JBCC hourly load, hourly generation, monthly distribution service tariff rates, and hourly and monthly/annual prices in wholesale markets for energy, capacity, and ancillary services in SEMA. Consequently, the analysis presented here should not be viewed as representative of the best or maximum value application of Ambri's storage technology in wholesale market or end-user contexts.

Even considering only the specific location/circumstance studied, there are numerous potential scenarios for use of storage technology at JBCC. The base itself is divided into several different distribution rate and power supply accounts, each with a different set of hourly load characteristics, total annual consumption, and monthly/seasonal peak load levels. Similarly, the current and future set of renewable generating resources (1) are spread throughout the base, (2) are connected both behind and in front of the meter, and (3) have different size, technology (wind/solar PV), efficiencies, and hourly generation profiles. Finally, current base tariffs for distribution service are subject to change in level and rate design (i.e., demand versus volumetric charges, or combinations of the two), and current contracts for wholesale energy supply are relatively short-term in nature and subject to renegotiation many times over the lifetime of battery installations.

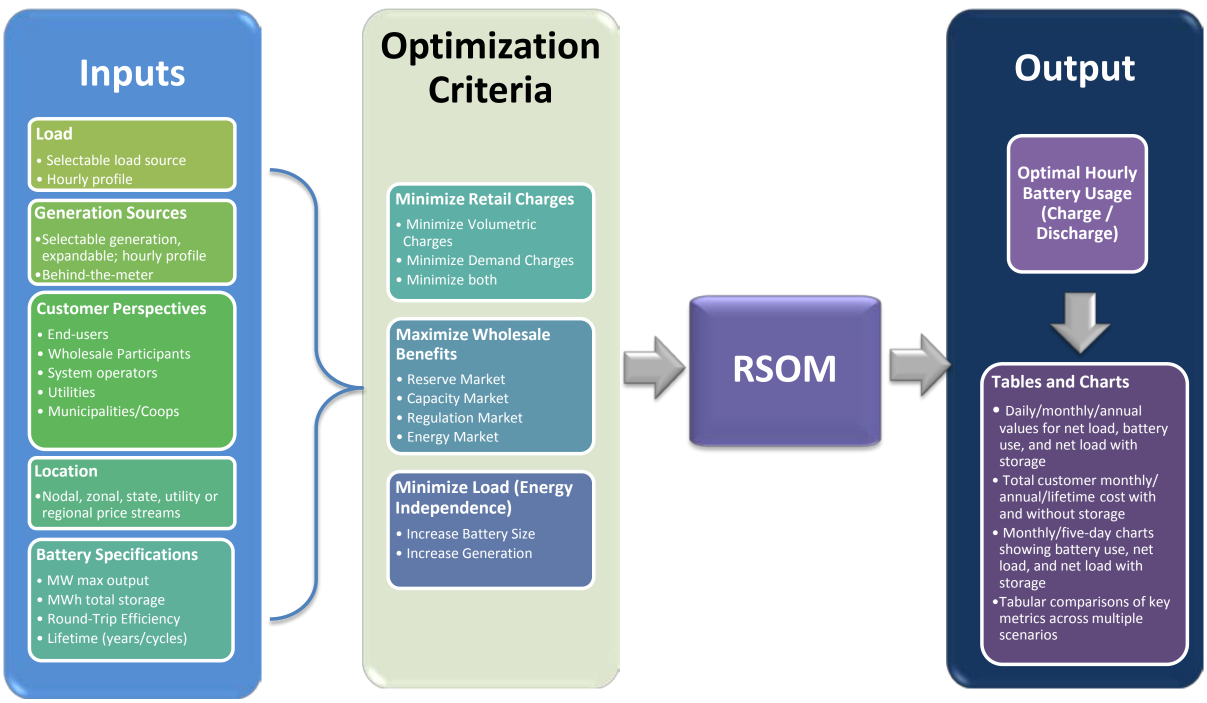
The purpose of the analysis, therefore, is to provide a representation of *potential* value associated with different levels of Ambri battery installation at JBCC, under various configurations combining load, generation, tariff levels/design, and optimization goals. In terms of optimization goals, the analysis estimates maximum cost/revenue value to the base considering wholesale market values and retail cost savings, and separately evaluates the use of Ambri storage on-base along with expanded on-site generation capacity to significantly increase the resilience of base critical mission operations to interruptions in power supply due to distribution and/or transmission system failures.

Optimization Model Description and Configuration Modes

Analysis Group's Renewable/Storage Optimization Model

Analysis Group developed the RSOM tool to analyze the potential value of a wide range of different storage technologies – with different operational and efficiency profiles – in a variety of possible wholesale market and retail service settings. Applications of the model can be tailored to analyze optimum storage technology application across a number of different contexts and conditions. As described in greater detail in the Appendix, 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 8, below.

Figure 8: Analysis Group's Renewable & Storage Optimization (RSOM) Flow Chart



Once configured, RSOM 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). Model output includes a number of metrics of interest to the user, as described further in the Appendix.

Configuration of RSOM for the Ambri/JBCC analysis

Project Vigilance will include prototype installations of Ambri's battery storage technology at JBCC, with the potential for eventual adding more capacity of Ambri storage installed at JBCC beyond the amounts identified for the current project. The purpose of our analysis is to configure a number of different battery sizes on base, combine it with base load, generation, and cost data, and identify the potential value of Ambri battery installations at JBCC from the perspective of JBCC's power security, renewable generation asset value, and overall base electricity costs over time.

Data on Ambri storage technology characteristics were obtained from Ambri. Historical data on hourly, monthly and annual peak load and consumption, distribution tariffs, and other electricity costs were obtained from JBCC or otherwise estimated in consultation with JBCC. JBCC also provided historical hourly data on output from existing wind turbines on the base, and size and efficiency expectations for new wind turbines and solar PV to be installed within the next couple years. The hourly generation profile for existing base wind facilities is used to model hourly generation of new wind capacity installed in 2013; an hourly solar PV generation profile for the northeast U.S. from National Renewable Energy Lab (NREL) was used to translate the expected future solar PV capacity into hourly generation profiles.

A number of additional assumptions and estimates were necessary for configuration of the base case analysis for the Ambri/JBCC installation, presented in Table 2 and described below and in more detail in the Appendix.

Table 2: RSOM Input and Options

Model Input and Specifications						
Load	**Generation**	**Battery Size**	**Wholesale Prices**	**Delivery Charge**	**Optimization Timeframe**	**Other Scenarios**
Base Grid Pave Paws Coast Guard Army Treatment Plants DSG Building	GE Turbines Fuhrlander Turbine Expansion Wind Solar Array	4 MWh 8 MWh 16 MWh *Note: The model can handle any size of battery*	2008 RTLMP 2009 RTLMP 2010 RTLMP 2011 RTLMP 2012 RTLMP 5-year average RTLMP (2008 - 2012)	Volumetric *- Rate determined by current tariffs where retail customers are charged based on a $/kWh rate.* Demand Charge *- A scenario where all delivery charges are collected through a demand charge rather than a volumetric charge.*	3-day optimization *- Optimization only considers a three-day timeframe for both the energy and demand optimizations.* Monthly optimization *- Optimization has perfect foresight for a month.*	Wholesale/Ancillary *- Considers the credits a battery of various sizes could receive in different wholesale and ancillary markets, such as regulation, capacity and reserves.* Critical Load *- For a given load, this scenario allows the user to test the size of battery needed for the base to be completely 'off-grid'.*

- Load and Tariffs: The base case analysis combines all load accounts on the base, including that associated with PAVEPAWS, the Base Grid, Coast Guard accounts, Army and Base Grid treatment plants, the DSG building, and additional miscellaneous accounts. For the purpose of the analysis we developed base-wide composite distribution rates based on actual NSTAR distribution service tariffs for each account. Results were reviewed assuming all distribution costs were collected through a demand charge and, separately, assuming distribution costs are collected through a mix of demand and volumetric-based charges. All generation was assumed to be fully net metered, such that distribution charges are calculated based on net load, and net export of power (i.e., when total base generation exceeds load) receives the combined wholesale and distribution rate, less certain minor tariff components consistent with NSTAR net metering tariff provisions.

- Generation: The base case analysis combines all current and expected future renewable generating assets installed on base. Specifically this includes four 1.5 MW GE wind turbines installed at the north end of the base, the 1.5 MW Fuhrlander turbine towards the south end of the base, and 6 MW of solar PV installed within the Base Grid. In the critical load analysis scenarios that scale up the renewable generation on base, the capacities of the new wind turbines and solar PV array are increased beyond current expectations, applying the same generation profiles for the scaled-up generation quantities.
- Wholesale Power Costs to JBCC: Accounts at JBCC rely on a mix of distribution company wholesale service and contracts for wholesale service by non-utility competitive retail suppliers. However, the existing wholesale power arrangements are short-term, subject to reissuance or renegotiation, and subsume considerations about the impact of on-base generation on net load within the wholesale pricing arrangements, since at the time wholesale contracts are negotiated competitive suppliers would base pricing on expectations of net supply obligations and wholesale market pricing. Consequently, the analysis applies actual hourly wholesale market prices as a proxy for base wholesale costs going forward. Specifically, in the base case we use SEMA zonal wholesale locational marginal prices (LMP) for 2012.[12]
- Wholesale Capacity and Ancillary Service Revenues: Payments for providing capacity, forward reserves, and regulation services were modeled as if the Ambri battery capacity participated in New England's wholesale markets for such services. Pricing for capacity was modeled at estimates of Forward Capacity Market (FCM) prices under at-criteria conditions (new capacity clears the market) and as a sensitivity at a forecast of FCM pricing with excess generation typical of current conditions. Prices for seasonal forward reserves and for providing regulation services were based on historical payments for such ancillary services over the past year.
- Battery Operations: Each tested size of the Ambri battery was modeled in the base case using three key operational parameters – round-trip (charge/discharge cycle) efficiency; maximum power output (in instantaneous MW output); and maximum storage capacity (in total MWh of discharge capability). The batteries were configured in a 4:1 ratio of total energy to power. For example, a "4 MWh" battery is capable of generating power at any given point in time in any amount up to 1 MW, and in continuous discharge starting from a fully-charged state can generate a total of 4 MWh of energy before needing to be recharged. This means that a 4 MWh battery can operate continuously at full power output (1MW) for 4 hours; similarly, it could operate continuously at 25% of its maximum power capability (0.25 MW) for 16 hours before needing to be recharged. Finally, in the charging state, there is an assumed efficiency of 75 percent. Thus, consumption of 1 MWh of energy (either from on-site generation or drawn from the grid) to charge the battery leads to stored energy in the battery of 0.75 MWh.

[12] The sensitivity of results to wholesale LMP assumptions was tested by also running the analysis using LMPs for each of the past five years (2008-2012), and for the average of these years.

(It should be noted, as discussed earlier, that whereas our analyses assume a set of *optimal* (e.g. highest roundtrip efficiency) and fixed charge, discharge and efficiency parameters, in reality Ambri batteries possess greater flexibility. For example, as modeled, a 4 MWh battery has a peak output constraint of 1MW per hour (for four hours) at 75% efficiency, but in practice this same battery could produce up a peak of 2 MW per hour (for two hours), albeit with a lower level of efficiency).

- Optimization Configuration: Battery use is configured assuming the battery operator seeks to optimize hourly charge/discharge of the battery over a 1-month billing period, in consideration of (a) expected load levels, (b) expected prices/costs, (c) expected power output from the renewable generation assets on base, and (d) the operating characteristics of the battery, discussed above. We also reviewed the same optimization assuming battery use is optimized over rolling 3-day periods, rather than over the full month. With this level of knowledge/foresight and within these constraints, the model seeks an optimal solution in which *hourly* battery use is dictated by the following coincident objectives:
  - Minimize monthly peak demand (to minimize demand-based charges);
  - Minimize monthly energy charges by exploiting energy arbitrage opportunities (i.e., use available battery space to charge when prices are low, and discharge when prices are high). This energy arbitrage opportunity will only overwrite the demand optimization battery use if the end result is lower total monthly electricity costs.

Results

Our analysis produced indicative results of Ambri battery value at JBCC under a number of potential scenarios. Clearly, the actual future value of Ambri batteries installed at JBCC will vary as a function of a number of factors discussed throughout this report, including:

1. Changes in the magnitude and shape of JBCC's electricity demand over the battery's lifetime;
2. The ultimate level of new renewable and traditional generation additions on-site;
3. The cost of fuel for operation of non-renewable back up generation (if needed);
4. The annual efficiency, capacity factors, and generation profiles of the wind and solar PV resources installed, and how such profiles match up with the profile of electricity demand;
5. The configuration/interconnection of various base electrical load accounts, and the degree of actual and virtual net metering of base renewable generation resources;
6. Battery price, performance and longevity;
7. NSTAR rate levels and rate designs;
8. Wholesale market designs and prices, and the eligibility of renewable resources and/or Ambri batteries to participate in energy, capacity, reserve, and regulation markets;
9. The negotiation of any power supply contracts to incorporate combined generation/battery net load characteristics into supply pricing;
10. Potentially significant bulk power system infrastructure changes that could lead to changes in locational marginal prices and tariff charges (such as the retirement of SEMA generation, or the addition of Cape Wind, as well as new investment in transmission facilities); and

11. Current and future state and DPU policies related to net metering, renewable portfolio standards, grid modernization, distribution rate design, customer-facing technologies, and time-varying pricing opportunities.

While all assumptions used in the analysis are rooted in recent historical hourly data on load, generation, and prices, and JBCC plans for near-term renewable generation additions, these assumptions may not necessarily match future conditions. Our analysis should not be viewed as a prediction of actual future values or specific outcomes. Instead, the results are indicative, order-of-magnitude approximations of *potential* future value, with the model results allowing for exploration of how the full spectrum of value streams (wholesale revenues, retail costs, critical load resilience/ independence) can help guide future exploration of installation objectives, timing, size, and pricing.

Based on the analysis, the installation of Ambri storage technology at JBCC has the potential to generate substantial cost and security/reliability benefits over time. As noted earlier, we tested different battery sizes in combination with different combinations of JBCC load and generation, rate structures, and wholesale market prices. Many results associated with different battery sizes and different metrics are presented in Appendix B.

Assuming a scenario involving the installation of a 16 MWh battery at JBCC, the results are as follows. Figures 9 and 10 demonstrate how the optimization operates on an hourly basis to achieve this outcome. Figure 9 shows a full month of charge/discharge outcomes, with the key result being a reduction in maximum monthly net load, with further optimization happening as a function of temporal differences in locational marginal prices. Figure10 shows this result in more detail for a single 5-day period, showing how battery operation affects the net JBCC load (that is, net of both renewable generation and battery activity) on an hourly basis.

Figure 9: RSOM Monthly Results

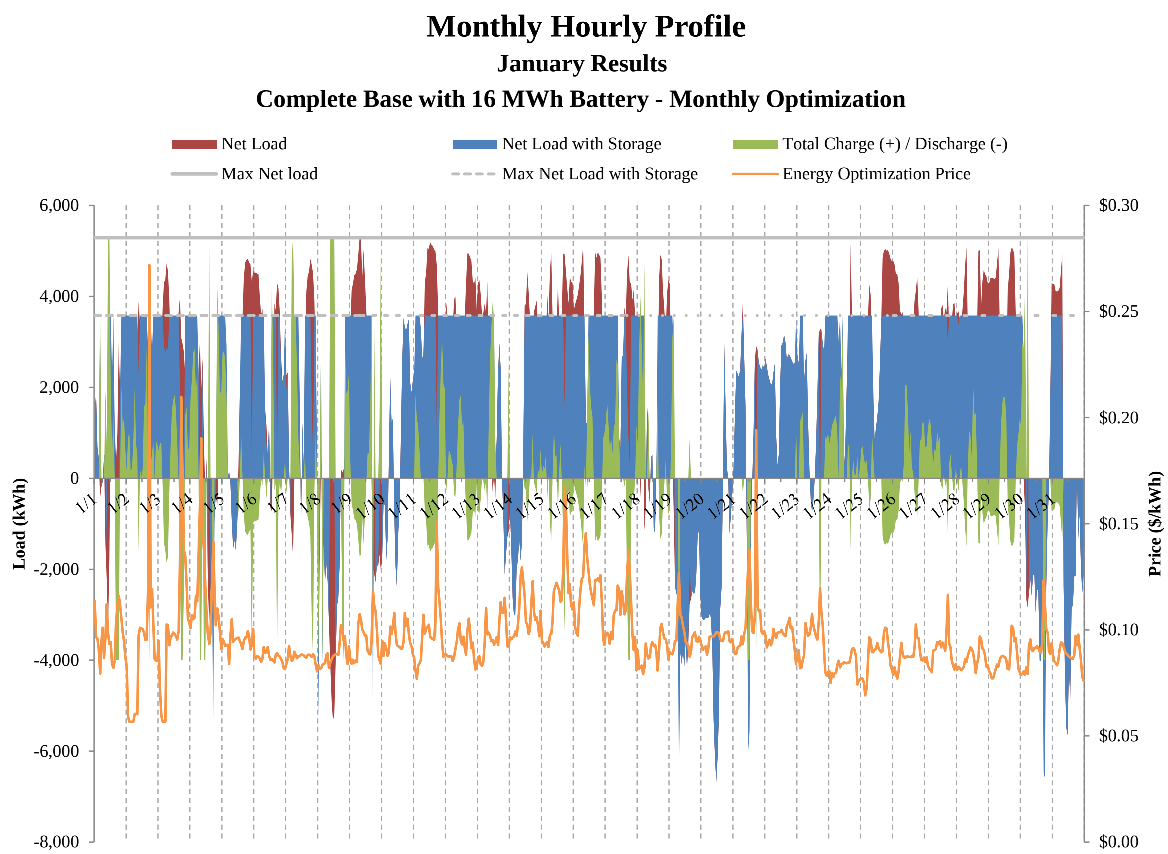
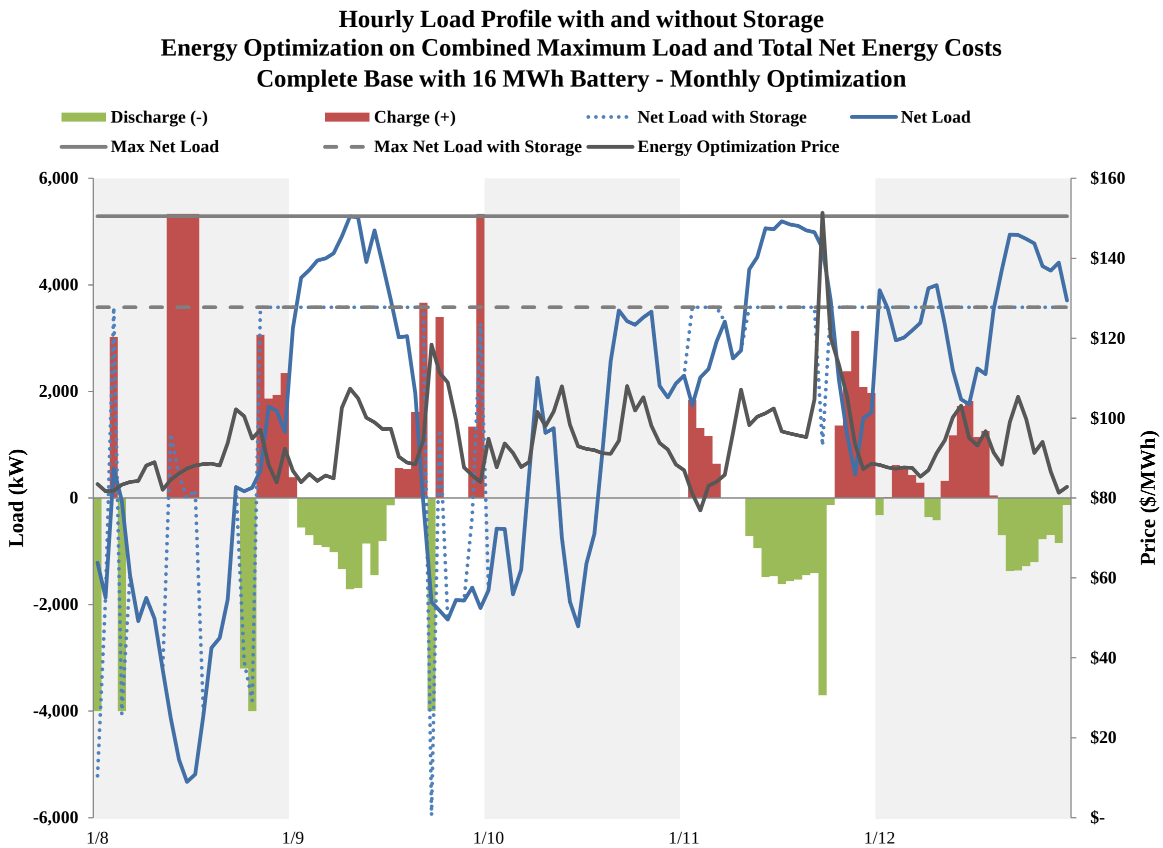


Figure 10: RSOM Model Select Daily Results



Focusing only on JBCC electricity bills, battery use could generate savings in electricity costs over an assumed 20-year battery life of up to almost $9.5 million, or roughly 23% of estimated JBCC retail electricity costs. While storage costs are not assessed, these savings may be used to evaluate the net cost of expanding battery installations. This estimate is based on full-base representations of load, renewable generation, and current prices for supply and distribution rates (assuming distribution costs are collected through demand charges). It represents primarily the operation of batteries to minimize monthly peak load, and thus reduce demand charges, along with use of remaining battery capacity to capture value through price arbitrage on wholesale supply costs.[13]

[13] Savings on wholesale supply costs are modeled using hourly locational marginal prices in the Southeastern Massachusetts load zone. While JBCC accounts typically do not pay for supply at hourly rates, savings based on LMPs are a reasonable proxy for the long-term value of managing net load through battery/renewables optimization, and obtaining more favorable supply contract pricing as a result of the optimized net load profile.

Table 3: RSOM Annual Results

Monthly Optimization, Demand-Based Delivery Charges
Lifetime Savings: 16 MWh Battery, Full Base

	Average Peak Demand (kW)	Electricity Costs		
		Supply	Delivery	Total
Without Battery	5,182	$ 10,330,278	$ 29,796,869	$ 40,127,146
With Battery	3,770	$ 9,036,650	$ 21,681,485	$ 30,718,135
Difference	**-1,411**	**$ (1,293,627)**	**$ (8,115,384)**	**$ (9,409,011)**
Percent Difference	**-27.2%**	**-12.5%**	**-27.2%**	**-23.4%**

Additional revenue generation in wholesale markets is a potentially significant value stream that should also be considered. JBCC does not currently participate as a supplier in wholesale electricity markets, and typically obtains wholesale supply through default service with the local utility and/or negotiated near-term contracts with competitive suppliers. However, the analysis demonstrates that posturing the battery for participation in wholesale markets could generate significant additional returns (which if credited to the base's electric accounts would further reduce total energy costs). The Ambri battery has operational characteristics that could enable it to participate in competitive wholesale markets for capacity, forward reserves, and regulation service.

Based on a battery size of 16 MWh and recent historical or expected future prices in New England's wholesale markets, participation in wholesale markets would have the potential to add up to approximately another $24 million over the battery life – about twice the value from a retail cost perspective. It is possible that the use of the battery for participation in wholesale markets would diminish to some extent its capacity for mitigating retail costs (and vice-versa), but this would depend on market rules, battery use objectives, typical battery charge/discharge cycle timing (based on load and generation), and load and generation forecasting capacity. To the extent that revenue generation would be fully additive to retail cost savings, installation of 16 MWh of Ambri batteries at JBCC could generate a total reduction in base energy costs over 20 years of over $34 million. Ideally, JBCC would evaluate whether and how to operate the batteries to capture as much of both revenue streams as possible, and to maximize battery value based on its best and highest value in wholesale

Table 4: RSOM Wholesale Market Results

Prices and Projected Payments for Ancillary Services in ISO-NE

	$/MW - Month	Projected Payments, 20 years [1]		
		4 MWh Battery	8 MWh Battery	16 MWh Battery
Regulation [2]	$ 16,236	$ 3,896,540	$ 7,793,080	$ 15,586,161
Capacity / Reserve Payments; New Entry [3]	$ 8,870	$ 2,128,800	$ 4,257,600	$ 8,515,200
Capacity / Reserve + Regulation Payments; New Entry [4]		**$ 6,025,340**	**$ 12,050,680**	**$ 24,101,361**

Notes:
[1] Projected annual payments assume full Battery capacity as listed is reserved for ancillary services.
[2] Based on total payments for regulation service of $11.6 million in 2012, and the average hourly regulation requirement of 59.54 MW. The average $/MW - Month was calculated by ($11.6 Million) / (59.54 MW) / (12 months).
[3] This payment represents the maximum credit a participant could receive given their participation in *both* the New England Forward Reserves and Capacity Markets in the event that new entry clears the market. The average price for Forward Reserves in the New England Wholesale markets was calculated by averaging the market clearing price in the forward reserve auctions from Summer 2013, and Winter 2013-2014. The estimated forward capacity payments given new entry by Brattle Group ("ISO-NE Offer Review Trigger Prices 2013 Study," September, 2013).
[4] At current levels (i.e. for the commitment period 2016-2017), total projected payments for participation of a 16 MWh battery in Reserve, Capacity, and Regulation Markets would amount about $8.5 million.

markets, retail bills, or both.

As battery size changes, so do the total annual and lifetime savings: for a battery of 8 MWh, lifetime savings are approximately $7 million, or 17%; for a battery of 4 MWh, lifetime savings are approximately $5 million, or 12%. Charts showing full results for all scenarios are provided in Appendix B.

Table 5: RSOM Summary Results

Total Cost and Battery Savings
Month Combined Optimization Annual Results
Delivery Price as Demand Charge

Total Costs without Battery	Annual	Lifetime
	$ 2,006,357	$ 40,127,146
Savings from Battery [1]		
4 MWh Battery	$ 245,692 12.2%	$ 4,913,846 12.2%
8 MWh Battery	$ 348,966 17.4%	$ 6,979,313 17.4%
16 MWh Battery	$ 470,451 23.4%	$ 9,409,011 23.4%

Notes:
[1] These savings amounts are calculated by subtracting the electricity costs with the battery from the baseline electricity costs without the battery.

Table 6: RSOM Summary Results

Total Cost and Battery Savings
Monthly Combined Optimization Annual Results
Delivery Price as Volumetric

Total Costs without Battery	Annual	Lifetime
	$ 2,006,357	$ 40,127,146
Savings from Battery [1]		
4 MWh Battery	$ 95,977 4.8%	$ 1,919,546.09 4.8%
8 MWh Battery	$ 133,531 6.7%	$ 2,670,618 6.7%
16 MWh Battery	$ 176,601 8.8%	$ 3,532,024 8.8%

Notes:
[1] These savings amounts are calculated by subtracting the electricity costs with the battery from the baseline electricity costs without the battery.

Combining battery storage with on-base renewable generation is most effective in reducing monthly peak demand charges. The base case analysis presents results assuming that all distribution costs are collected through demand charges, to provide an upper-bound estimate on savings under potential rate designs that could be in place over the life of the battery. However, current rate designs collect distribution costs through a combination of demand and volumetric components, as well as customer charges and in some cases credits for JBCC's management of sub-metered accounts on base. The RSOM tool was also used to estimate battery value under a mix of demand and volumetric components consistent with current rate structures. The value is lower than the base case results by a meaningful amount, essentially reflecting the fact that the charging of the battery for lowering monthly peak load (to capture demand charge savings) comes at a volumetric charge cost, given the assumed charge/discharge cycle efficiency of 75 percent. For a 16 MWh battery total lifetime savings in retail costs are approximately $3.5 million, or 9%.

The RSOM tool was also used to assess the degree of grid independence that could be achieved through various combinations of battery storage and renewable generation. JBCC has a unique interest in energy storage, in part due to the existence of mission critical load on the base. Since storage can play a role in protecting against potential power outages, the model was used to analyze the question of how to optimally size renewable generation and battery capacity to achieve full separation from the surrounding grid – or alternatively minimize the number of hours or days when non-renewable backup generation would be needed – while still meeting the critical load on the base. The results are shown in Table 7 and Figure 11. JBCC provided data on the level and profile of JBCC load required for mission critical operations – that is, the level of load that can not be interrupted, or for which there must be alternative on-site backup generation to ensure continued operations in the event of an outage on the surrounding grid. This is referred to as *net critical load*.

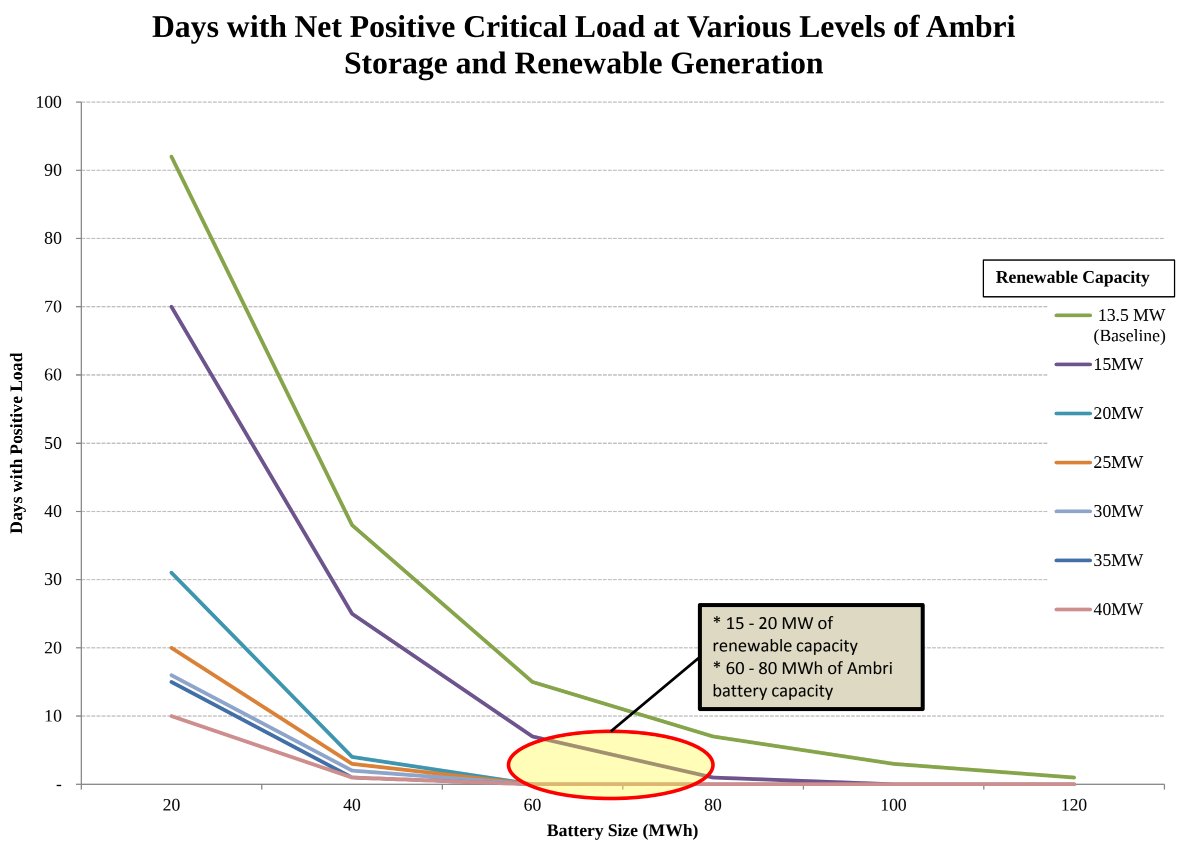
At the currently-expected level of renewable generation on the base (13.5 MW), it would take over 120 MWh of Ambri battery capacity to eliminate days with positive net critical load. However, RSOM was used to review how this result changes with different levels of renewable capacity on base. For this purpose, we added capacity above the Base Case level (13.5 MW) in equal increments of wind and solar PV capacity. As can be seen in Table 7, at just an additional 1.5 MW of renewable capacity (15 MW total), 80 MWh of Ambri storage capacity would reduce the number of days with net positive critical load to 1; with 60 MWh of storage capability and 20 MW of renewable capacity, there are zero days (and zero hours – see additional table results in the Appendix) with positive net critical load.

In effect, this analysis suggests that JBCC could approach critical load grid independence with on the order of between 15 and 20 MW of renewable capacity, combined with approximately 60 to 80 MWh of Ambri storage capacity. JBCC may wish to consider further analysis to determine whether this represents a "sweet spot" of combined renewable and Ambri storage capability that meets all of the military command's multiple objectives with respect to energy/emission goals, economic/cost saving mandates, and mission critical load security/independence needs. Ultimately, the key decision on installations should balance a combination of renewable generation, storage capacity, and an ongoing source of backup generation for low-probability, severe weather or other grid interruption events. In this sense, the analysis conducted here is more indicative of achieving a desired level of critical mission resilience and minimizing the operation of backup generation (and associated fuel costs), rather than achieving full independence from the grid.

Table 7: RSOM Critical Load Summary Results

	Days with Positive Net Load						
	Renewable Generation Capacity (MW)						
Battery Size (MWh)	13.5 MW (Baseline)	15MW	20MW	25MW	30MW	35MW	40MW
20	92	70	31	20	16	15	10
40	38	25	4	3	2	1	1
60	15	7	-	-	-	-	-
80	7	1	-	-	-	-	-
100	3	-	-	-	-	-	-
120	1	-	-	-	-	-	-

Figure 11: RSOM Model Critical Load Results



APPENDICES

A. **RSOM Tool**

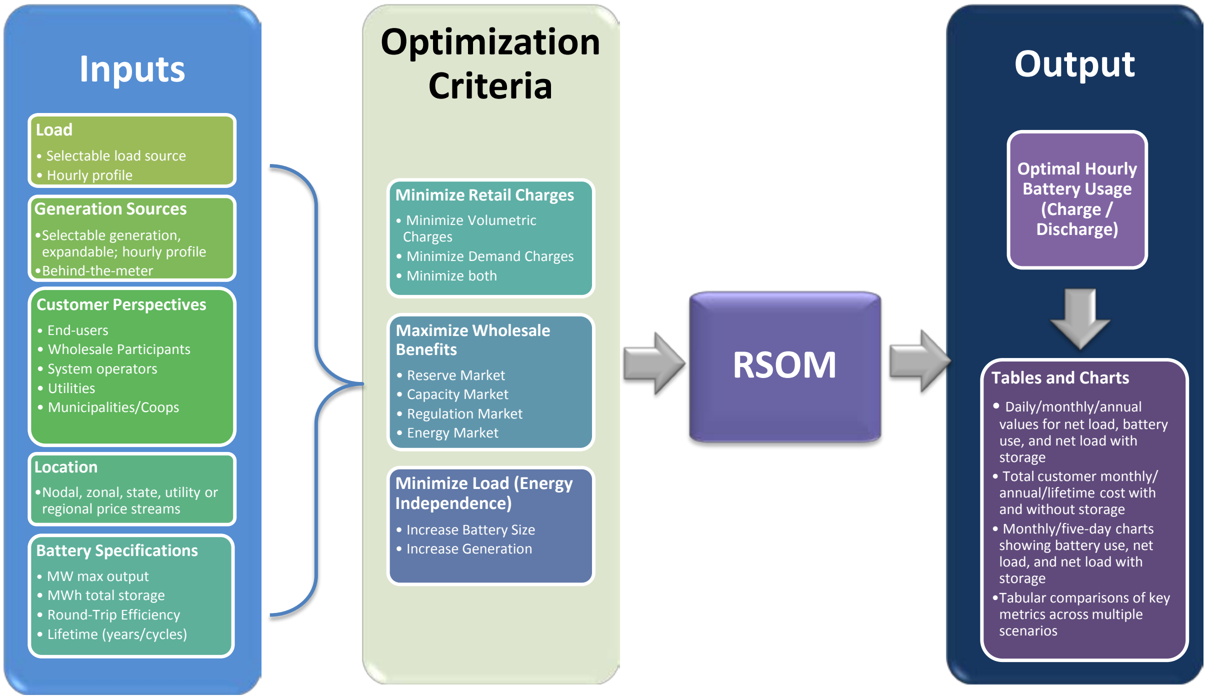
B. **Charts/Tables/Graphs for all battery sizes modeled; additional tables/charts on net critical load analysis**

A. RSOM

Analysis Group developed the RSOM tool to analyze the potential value of a wide range of different storage technologies – with different operational and efficiency profiles – in a variety of possible wholesale market and retail service settings. Applications of the model can be tailored to analyze optimum storage technology application 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, including at least the following:

- *Storage Technology Characteristics and Operating Modes*: The RSOM tool is structured around a flexible set of storage technology characteristic inputs, including size (MW of maximum power output and MWh of total storage capacity); lifetime (in years or cycles); charge/discharge cycle efficiency and efficiency degradation over time; charge/discharge rate (in MWh/hour or more granular increments); etc.
- *Customer Segments*: RSOM may be configured to analyze storage value from the perspective of multiple potential interests, including end-use customers (with or without owned, behind the meter generation); wholesale market participants (stand-alone or in combination with generation assets); regional system operators interested in managing ancillary service needs; vertically-integrated or distribution-only investor-owned utilities; municipalities, coops, or institutional interests; etc.
- *Market Structures*: RSOM may be applied in the context of fully-regulated, vertically-integrated utility industry structures, fully-competitive wholesale and retail markets, or some mixture of the two.
- *States and Regions*: RSOM inputs are flexible enough to incorporate any nodal, zonal, state, utility, or regional hourly, monthly, or annual tariff or wholesale market (energy, capacity, ancillary services) price streams.
- *Load Characteristics*: RSOM models customer annual energy consumption, monthly/annual peak loads, and load profiles on an 8760 hourly basis.
- *Generation Portfolios*: RSOM generation inputs are structured to incorporate customer-specific 8760 hourly generation output data, or to create 8760 generation profiles based on capacities, annual generation, and representative technology generation profiles.
- *Load/Generation Configurations*: RSOM can be configured to evaluate numerous combinations of load accounts and generating resource assets, provided load and generation profiles are entered separately in the model. The model user can then select various combinations of generating sources, load accounts, and battery sizes as scenarios for optimization analysis.
- *Host Objectives and Different Value Streams*: RSOM may be configured to evaluate optimal battery use based on a user-selected set of potential value streams. For example, the user may select only monthly bill minimization, only wholesale market revenue generation, or various combinations of such objectives. The model also may be tailored to achieve different objectives, such as minimization of outage risk in microgrid (grid independence) mode under various combinations of load and generation assets.

Figure A-1: Analysis Group's Renewable & Storage Optimization (RSOM) Tool Flow Chart



Once configured, the RSOM tool evaluates storage technology value through simulations of battery-use optimization, based on load, generation, price, and tariff data, subject to constraints on battery operations (size/storage capacities, charge/discharge rates and efficiency, etc.), and pursuant to user optimization objectives (such as minimum distribution, wholesale, or all-in costs; maximum wholesale asset revenue generation, or minimum hours/quantities of potential loss of power to total or critical loads. The optimization solves for hourly battery operation modes (charge, discharge, rate, endpoint) that meet the optimization objective over the selected time period (in our analysis, we select a one-month optimization timeframe).

The RSOM model automatically generates hourly data on load, generation, net load, battery usage, and battery-net load (i.e., load net of generation and battery use); this data may be easily used to generate charts and metrics of interest with respect to customer and battery operations. In addition, RSOM generates a number of additional data, tables, and charts. Specific output data, tables, and charts include some or all of the following (depending on customer circumstances and model configuration), for each scenario. See Table A-1.

1. Hourly net load (load minus generation);
2. Hourly storage technology use (MWh consumed or discharged by, battery);
3. Hourly net load with storage (load minus generation plus/minus storage technology use);
4. Daily/monthly/annual values for net load, battery use, and net load with storage;
5. Monthly and annual wholesale market revenues (capacity, reserves, regulation);
6. Total customer monthly, annual, or lifetime costs/bills without storage, with storage, and difference (in dollars and percent), broken down by energy/wholesale costs, and distribution costs (total, or where applicable divided into demand and volumetric components);

7. Tabular comparisons of results by key metric across multiple scenarios;
8. Charts of monthly and annual costs and savings with and without storage; and
9. Customizable five-day and monthly charts showing hourly load, net load (i.e. net of generation), battery usage, and battery-net load (i.e., load net of generation and battery usage); for such charts, the time period of interest is selected by the user.

Table A-1: RSOM Output

Model Output	
Tables	**Charts**
Costs with and without Battery	Total Costs and Savings Bar Chart
Delivery	Monthly Peak Load Bar Chart
Energy	Monthly Load and Battery Usage chart
Demand	- *Select month to view*
Savings	Five-day Load and Battery Usage chart
Absolute	- *Select timeframe to view*
Percentage	
Lifetime Savings (20 yrs.)	

B. Charts/Tables/Graphs for all battery sizes modeled; additional tables/charts on net critical load analysis

1. Results from full base optimization of retail electricity prices using a 4 MWh Ambri battery

Table C-1

Annual Results
Complete Base with 4 MWh Battery - Monthly Optimization
Delivery Price as Demand Charge

	Average Peak Demand (kW)	Electricity Costs			
		Delivery	Energy	Demand	Total
Without Battery	5,182	$ 851,791	$ 516,514	$ 638,052	$ 2,006,357
With Battery	4,394	$ 722,340	$ 497,247	$ 541,079	$ 1,760,665
Difference	**-788**	**$ (129,451)**	**$ (19,267)**	**$ (96,974)**	**$ (245,692)**
Percent Difference	**-15.2%**	**-15.2%**	**-3.7%**	**-15.2%**	**-12.2%**

Table C-2

Annual Results
Complete Base with 4 MWh Battery - Monthly Optimization
Delivery Price as Demand & Volumetric Charge

	Total Usage (MWh)	Electricity Costs			
		Delivery	Energy	Demand	Total
Without Battery	14,347	$ 851,791	$ 516,514	$ 638,052	$ 2,006,357
With Battery	14,717	$ 872,055	$ 497,247	$ 541,079	$ 1,910,380
Difference	**370**	**$ 20,264**	**$ (19,267)**	**$ (96,974)**	**$ (95,977)**
Percent Difference	**2.6%**	**2.4%**	**-3.7%**	**-15.2%**	**-4.8%**

Figure A3-1

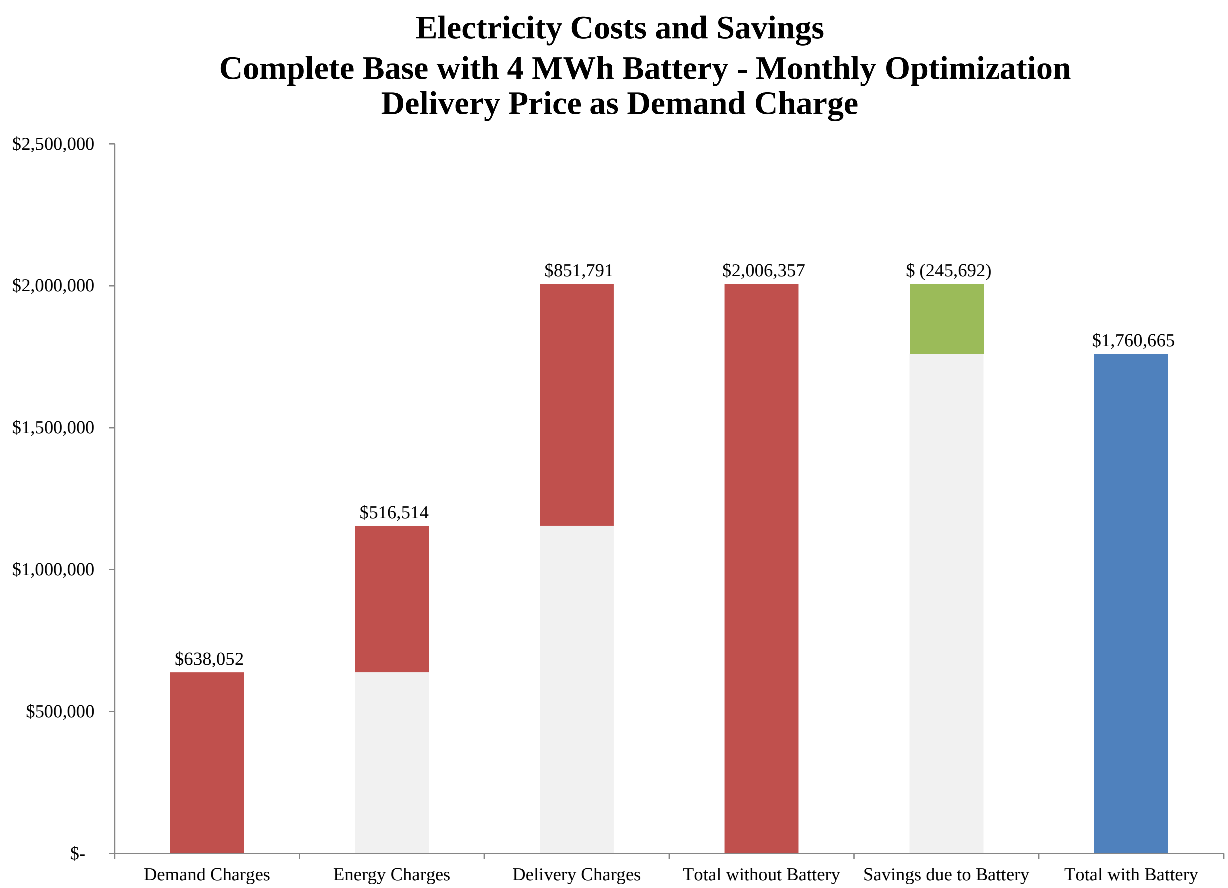

Electricity Costs and Savings
Complete Base with 4 MWh Battery - Monthly Optimization
Delivery Price as Demand Charge
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
$638,052
$516,514
$851,791
$2,006,357
$ (245,692)
$1,760,665
Demand Charges
Energy Charges
Delivery Charges
Total without Battery
Savings due to Battery
Total with Battery

Figure C-2

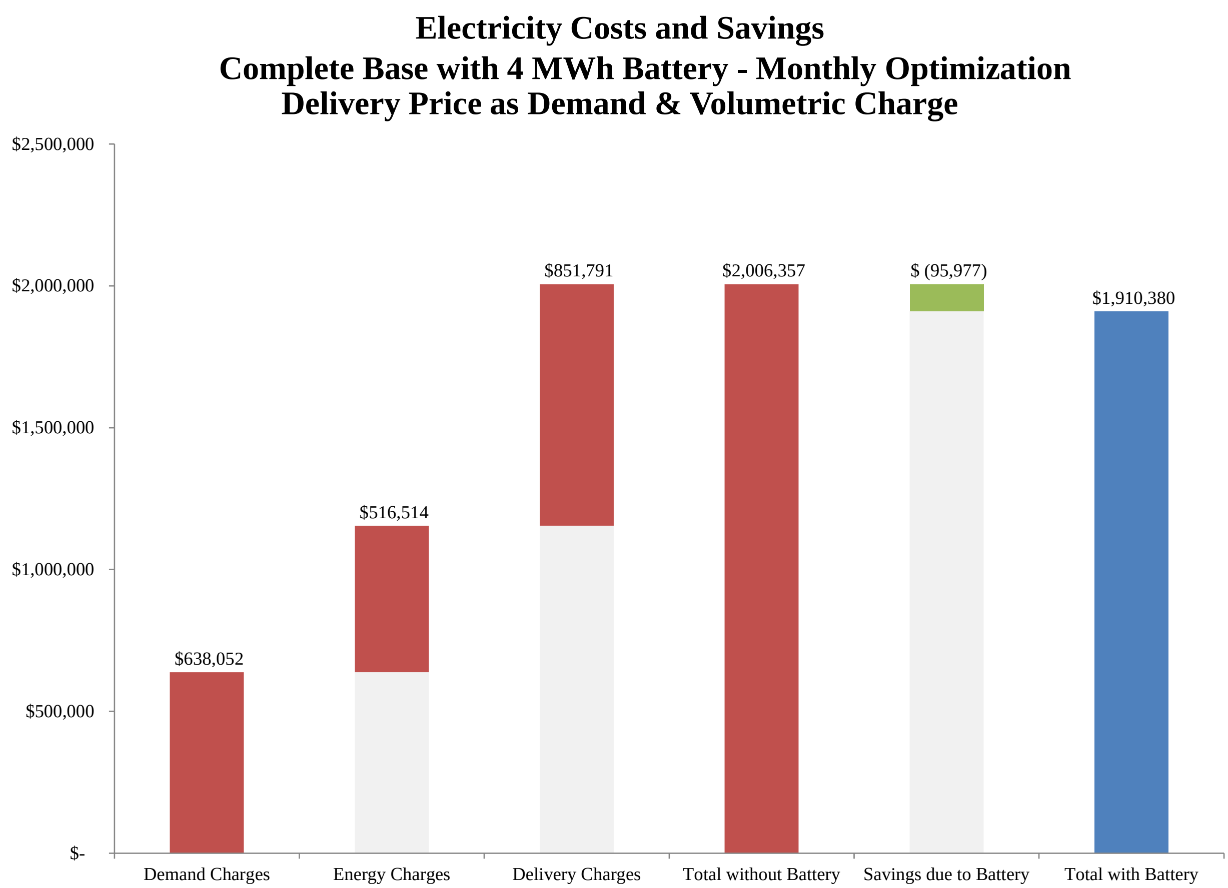

Electricity Costs and Savings
Complete Base with 4 MWh Battery - Monthly Optimization
Delivery Price as Demand & Volumetric Charge
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
$638,052
$516,514
$851,791
$2,006,357
$ (95,977)
$1,910,380
Demand Charges
Energy Charges
Delivery Charges
Total without Battery
Savings due to Battery
Total with Battery

Figure C-3

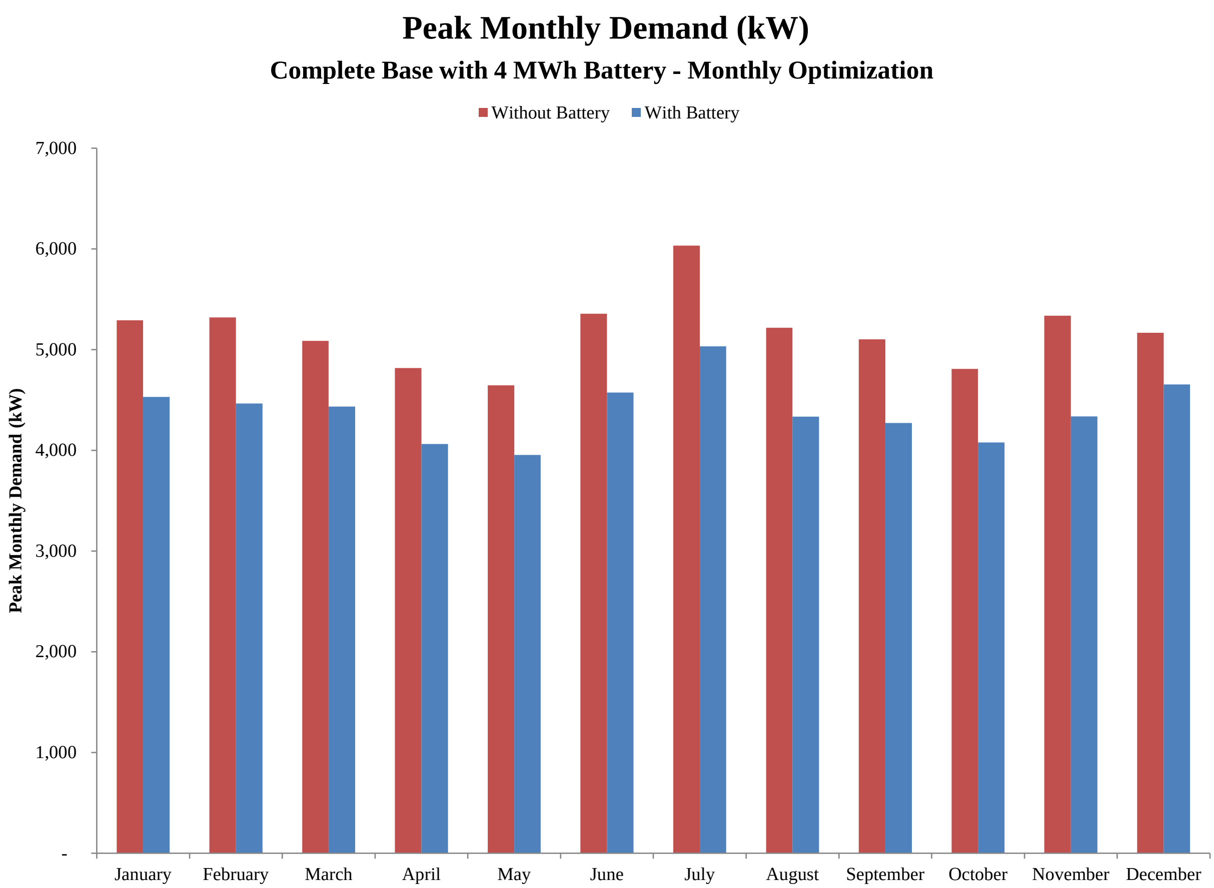

Peak Monthly Demand (kW)
Complete Base with 4 MWh Battery - Monthly Optimization
Without Battery
With Battery
Peak Monthly Demand (kW)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-
January
February
March
April
May
June
July
August
September
October
November
December

Figure C-4

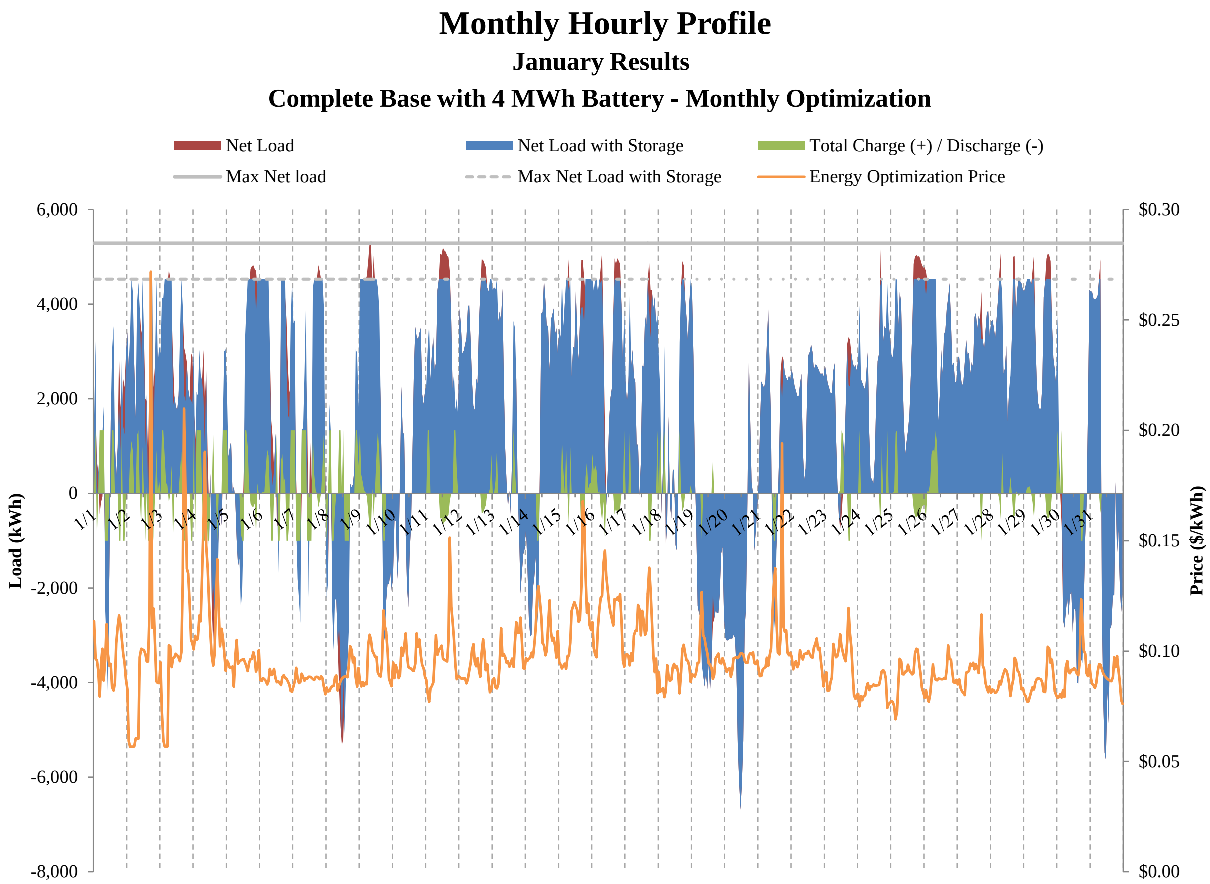
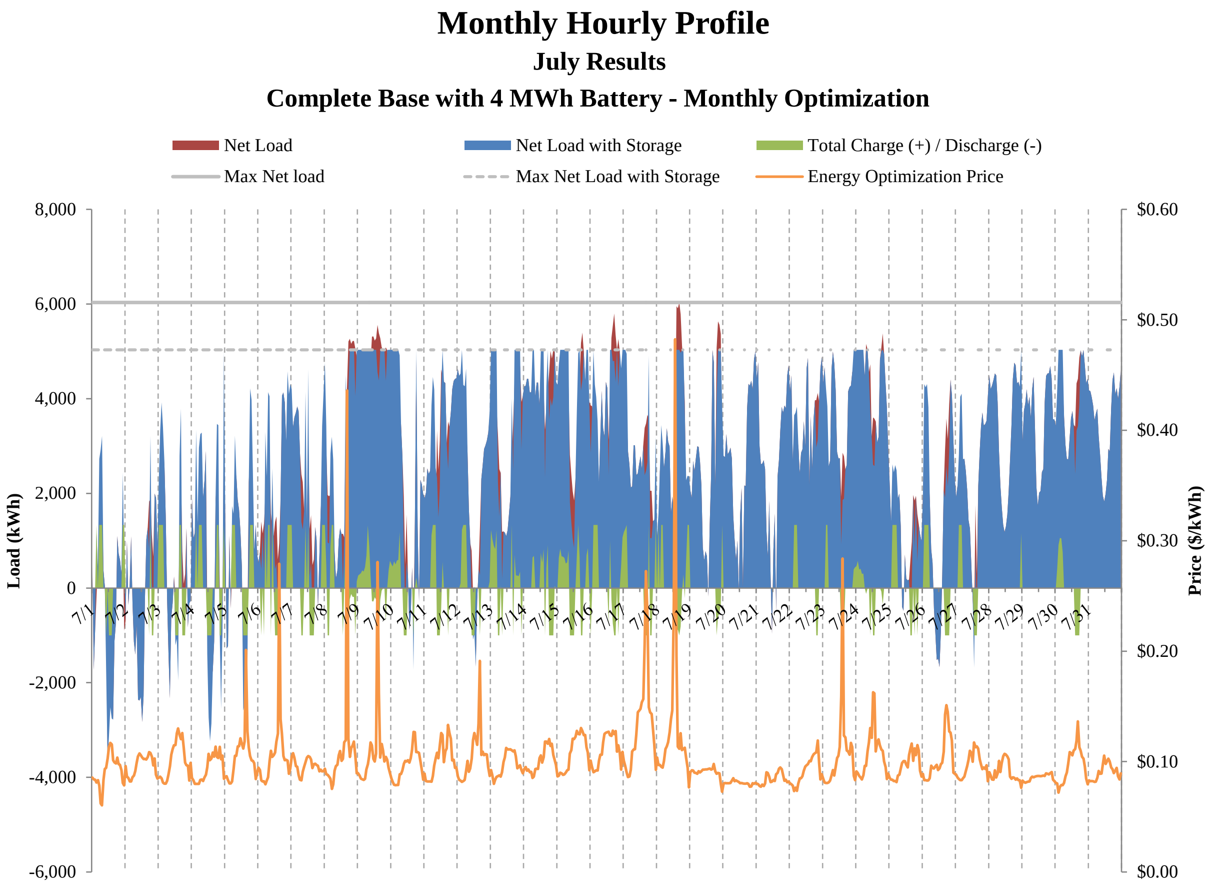

Monthly Hourly Profile
January Results
Complete Base with 4 MWh Battery - Monthly Optimization
Net Load
Net Load with Storage
Total Charge (+) / Discharge (-)
Max Net load
Max Net Load with Storage
Energy Optimization Price
Load (kWh)
Price ($/kWh)
6,000
4,000
2,000
0
-2,000
-4,000
-6,000
-8,000
$0.30
$0.25
$0.20
$0.15
$0.10
$0.05
$0.00
1/1
1/2
1/3
1/4
1/5
1/6
1/7
1/8
1/9
1/10
1/11
1/12
1/13
1/14
1/15
1/16
1/17
1/18
1/19
1/20
1/21
1/22
1/23
1/24
1/25
1/26
1/27
1/28
1/29
1/30
1/31

Figure C-5


Monthly Hourly Profile
July Results
Complete Base with 4 MWh Battery - Monthly Optimization
Net Load
Net Load with Storage
Total Charge (+) / Discharge (-)
Max Net load
Max Net Load with Storage
Energy Optimization Price
Load (kWh)
Price ($/kWh)
8,000
6,000
4,000
2,000
0
-2,000
-4,000
-6,000
$0.60
$0.50
$0.40
$0.30
$0.20
$0.10
$0.00
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13
7/14
7/15
7/16
7/17
7/18
7/19
7/20
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29
7/30
7/31

2. Results from full base optimization of retail electricity prices using a 8 MWh Ambri battery

Table C-3

Annual Results
Complete Base with 8 MWh Battery - Monthly Optimization
Delivery Price as Demand Charge

	Average Peak Demand (kW)	Electricity Costs			
		Delivery	Energy	Demand	Total
Without Battery	5,182	$ 851,791	$ 516,514	$ 638,052	$ 2,006,357
With Battery	4,095	$ 673,206	$ 479,900	$ 504,286	$ 1,657,392
Difference	**-1,086**	**$ (178,585)**	**$ (36,614)**	**$ (133,766)**	**$ (348,966)**
Percent Difference	**-21.0%**	**-21.0%**	**-7.1%**	**-21.0%**	**-17.4%**

Table C-4

Annual Results
Complete Base with 8 MWh Battery - Monthly Optimization
Delivery Price as Demand & Volumetric Charge

	Total Usage (MWh)	Electricity Costs			
		Delivery	Energy	Demand	Total
Without Battery	14,347	$ 851,791	$ 516,514	$ 638,052	$ 2,006,357
With Battery	15,013	$ 888,640	$ 479,900	$ 504,286	$ 1,872,826
Difference	**666**	**$ 36,849**	**$ (36,614)**	**$ (133,766)**	**$ (133,531)**
Percent Difference	**4.6%**	**4.3%**	**-7.1%**	**-21.0%**	**-6.7%**

Figure C-6

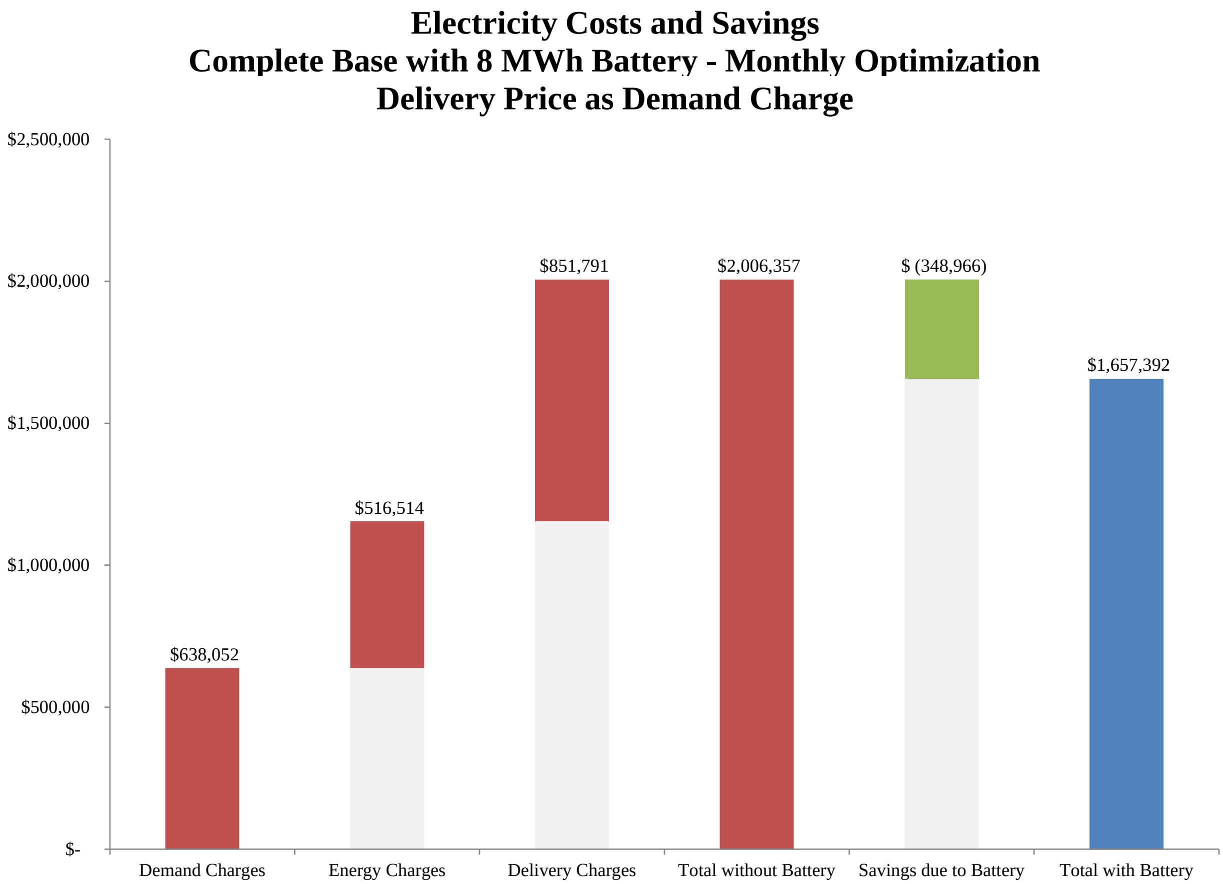

Electricity Costs and Savings
Complete Base with 8 MWh Battery - Monthly Optimization
Delivery Price as Demand Charge
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
$638,052
$516,514
$851,791
$2,006,357
$ (348,966)
$1,657,392
Demand Charges
Energy Charges
Delivery Charges
Total without Battery
Savings due to Battery
Total with Battery

Figure C-7

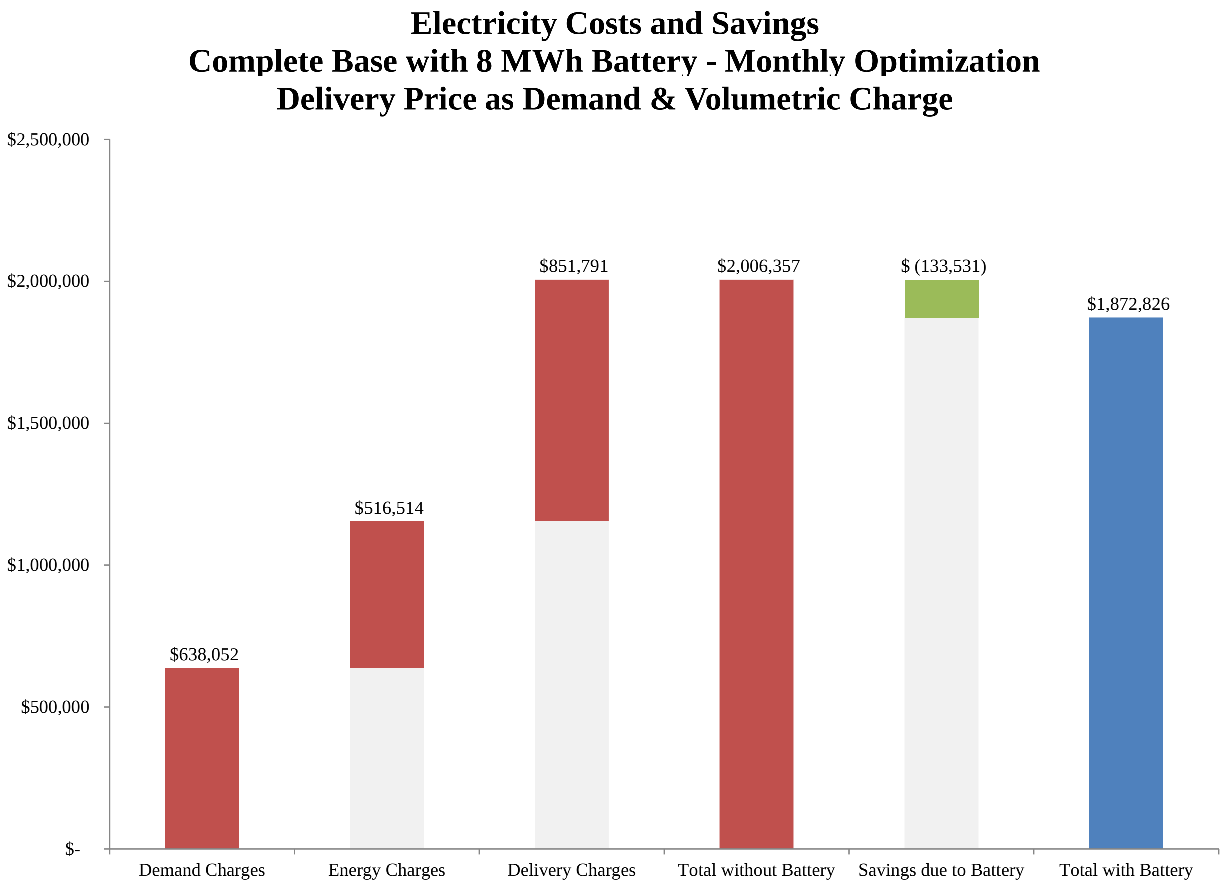

Electricity Costs and Savings
Complete Base with 8 MWh Battery - Monthly Optimization
Delivery Price as Demand & Volumetric Charge
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
$638,052
$516,514
$851,791
$2,006,357
$ (133,531)
$1,872,826
Demand Charges
Energy Charges
Delivery Charges
Total without Battery
Savings due to Battery
Total with Battery

Figure C-8

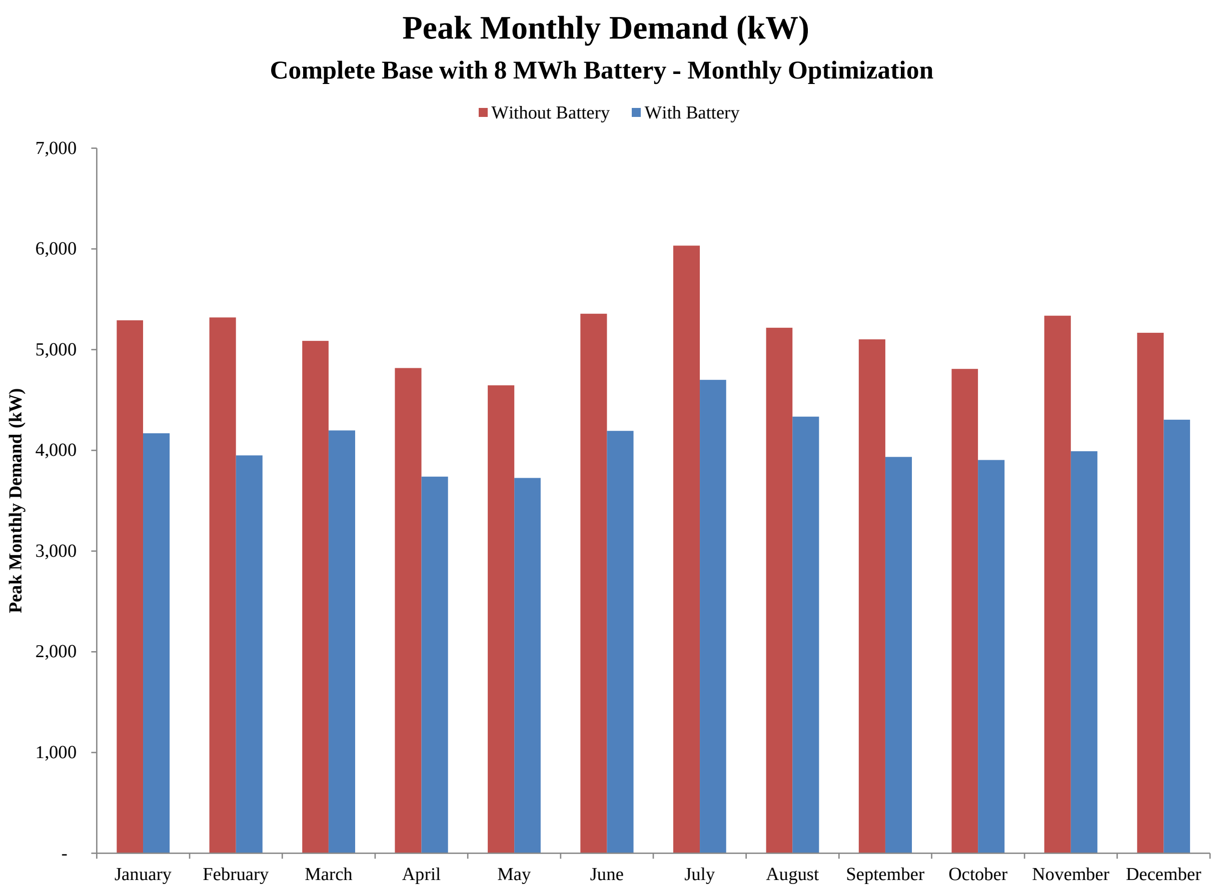

Peak Monthly Demand (kW)
Complete Base with 8 MWh Battery - Monthly Optimization
Without Battery
With Battery
Peak Monthly Demand (kW)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-
January
February
March
April
May
June
July
August
September
October
November
December

Figure C-9

Monthly Hourly Profile

January Results

Complete Base with 8 MWh Battery - Monthly Optimization

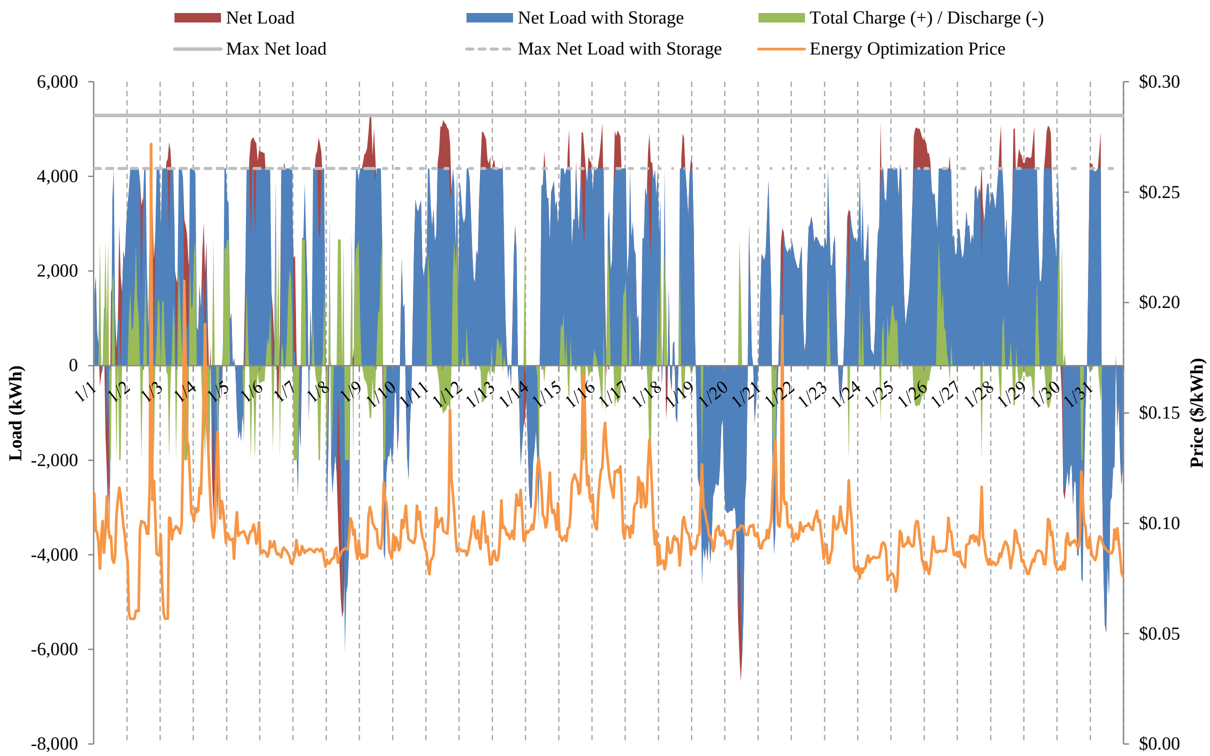
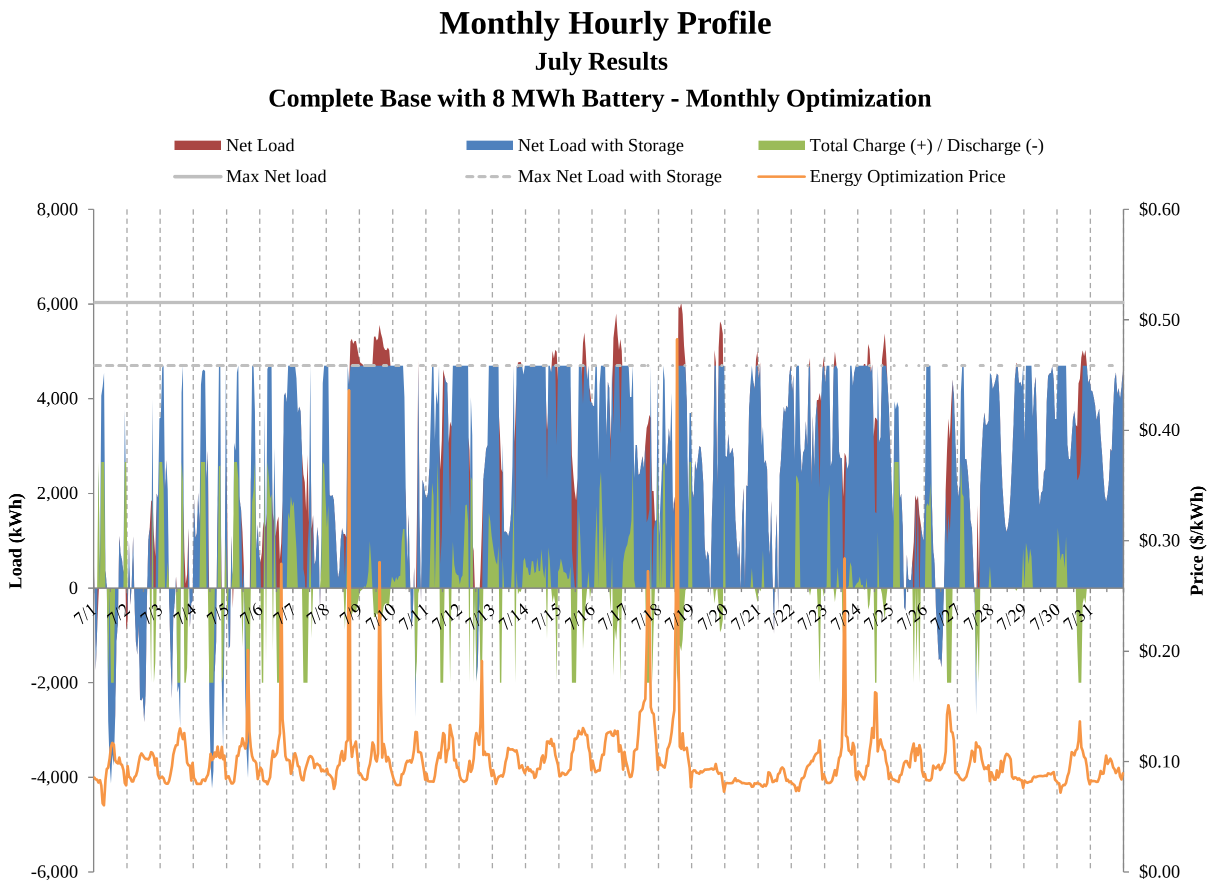


Figure C-10


Monthly Hourly Profile
July Results
Complete Base with 8 MWh Battery - Monthly Optimization
Net Load
Net Load with Storage
Total Charge (+) / Discharge (-)
Max Net load
Max Net Load with Storage
Energy Optimization Price
Load (kWh)
Price ($/kWh)
8,000
6,000
4,000
2,000
0
-2,000
-4,000
-6,000
$0.60
$0.50
$0.40
$0.30
$0.20
$0.10
$0.00
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13
7/14
7/15
7/16
7/17
7/18
7/19
7/20
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29
7/30
7/31

3. Results from full base optimization of retail electricity prices using a 16 MWh Ambri battery

Table C-5

Annual Results
Complete Base with 16 MWh Battery - Monthly Optimization
Delivery Price as Demand Charge

	Average Peak Demand (kW)	Electricity Costs			
		Delivery	Energy	Demand	Total
Without Battery	5,182	$ 851,791	$ 516,514	$ 638,052	$ 2,006,357
With Battery	3,770	$ 619,779	$ 451,833	$ 464,295	$ 1,535,907
Difference	**-1,411**	**$ (232,012)**	**$ (64,681)**	**$ (173,757)**	**$ (470,451)**
Percent Difference	**-27.2%**	**-27.2%**	**-12.5%**	**-27.2%**	**-23.4%**

Table C-6

Annual Results
Complete Base with 16 MWh Battery - Monthly Optimization
Delivery Price as Demand & Volumetric Charge

	Total Usage (MWh)	Electricity Costs			
		Delivery	Energy	Demand	Total
Without Battery	14,347	$ 851,791	$ 516,514	$ 638,052	$ 2,006,357
With Battery	15,435	$ 913,628	$ 451,833	$ 464,295	$ 1,829,756
Difference	**1,088**	**$ 61,837**	**$ (64,681)**	**$ (173,757)**	**$ (176,601)**
Percent Difference	**7.6%**	**7.3%**	**-12.5%**	**-27.2%**	**-8.8%**

Figure C-11

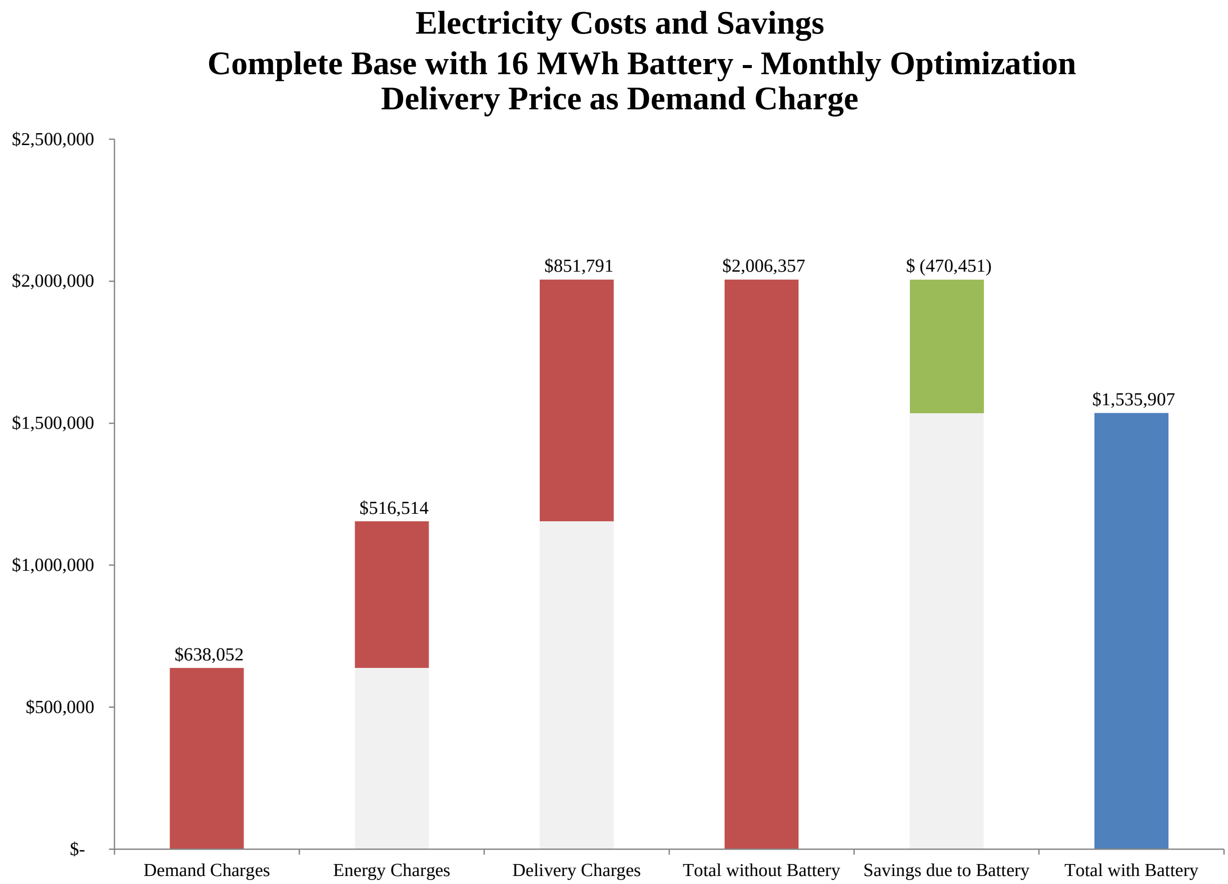

Electricity Costs and Savings
Complete Base with 16 MWh Battery - Monthly Optimization
Delivery Price as Demand Charge
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
$638,052
$516,514
$851,791
$2,006,357
$ (470,451)
$1,535,907
Demand Charges
Energy Charges
Delivery Charges
Total without Battery
Savings due to Battery
Total with Battery

Figure C-12

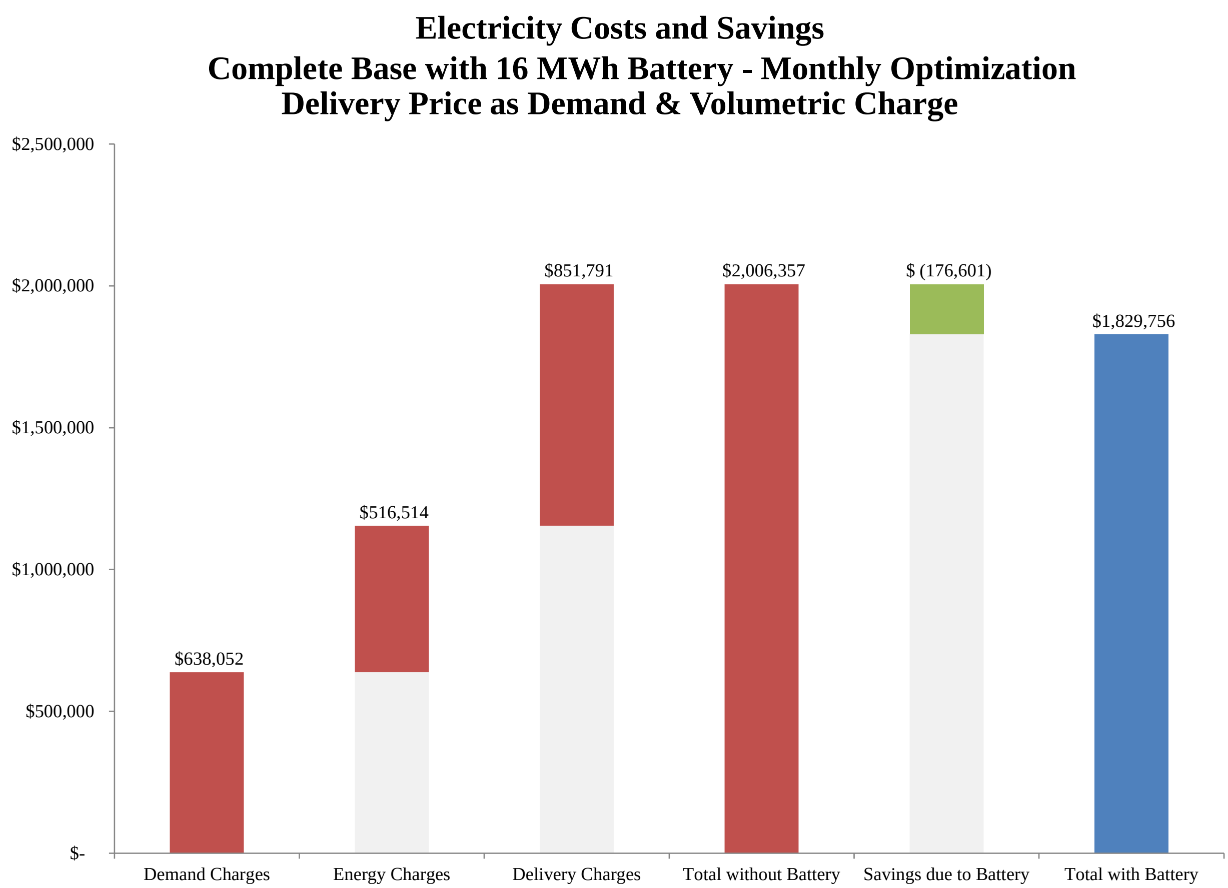

Electricity Costs and Savings
Complete Base with 16 MWh Battery - Monthly Optimization
Delivery Price as Demand & Volumetric Charge
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
$638,052
$516,514
$851,791
$2,006,357
$ (176,601)
$1,829,756
Demand Charges
Energy Charges
Delivery Charges
Total without Battery
Savings due to Battery
Total with Battery

Figure C-13

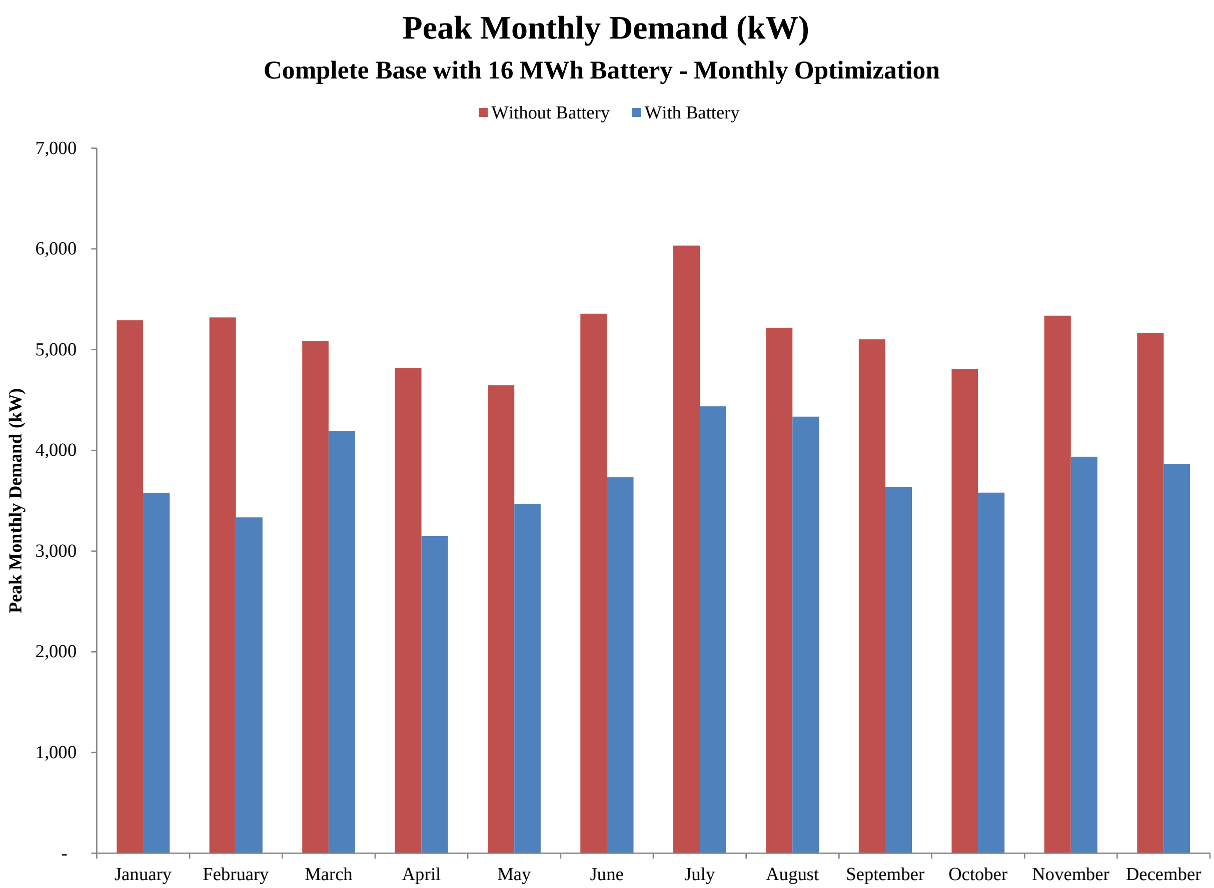
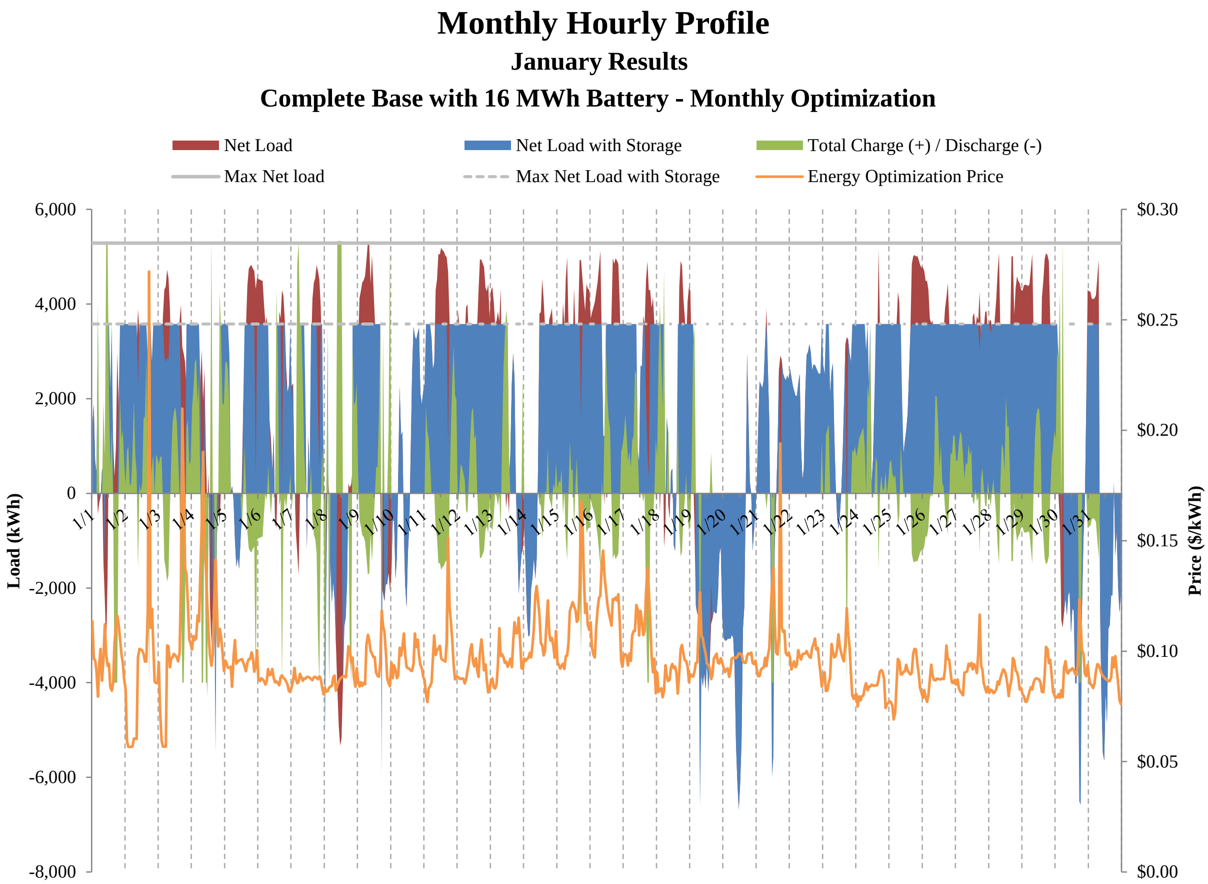

Peak Monthly Demand (kW)
Complete Base with 16 MWh Battery - Monthly Optimization
Without Battery
With Battery
Peak Monthly Demand (kW)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-
January
February
March
April
May
June
July
August
September
October
November
December

Figure C-14


Monthly Hourly Profile
January Results
Complete Base with 16 MWh Battery - Monthly Optimization
Net Load
Net Load with Storage
Total Charge (+) / Discharge (-)
Max Net load
Max Net Load with Storage
Energy Optimization Price
Load (kWh)
Price ($/kWh)
6,000
4,000
2,000
0
-2,000
-4,000
-6,000
-8,000
$0.30
$0.25
$0.20
$0.15
$0.10
$0.05
$0.00
1/1
1/2
1/3
1/4
1/5
1/6
1/7
1/8
1/9
1/10
1/11
1/12
1/13
1/14
1/15
1/16
1/17
1/18
1/19
1/20
1/21
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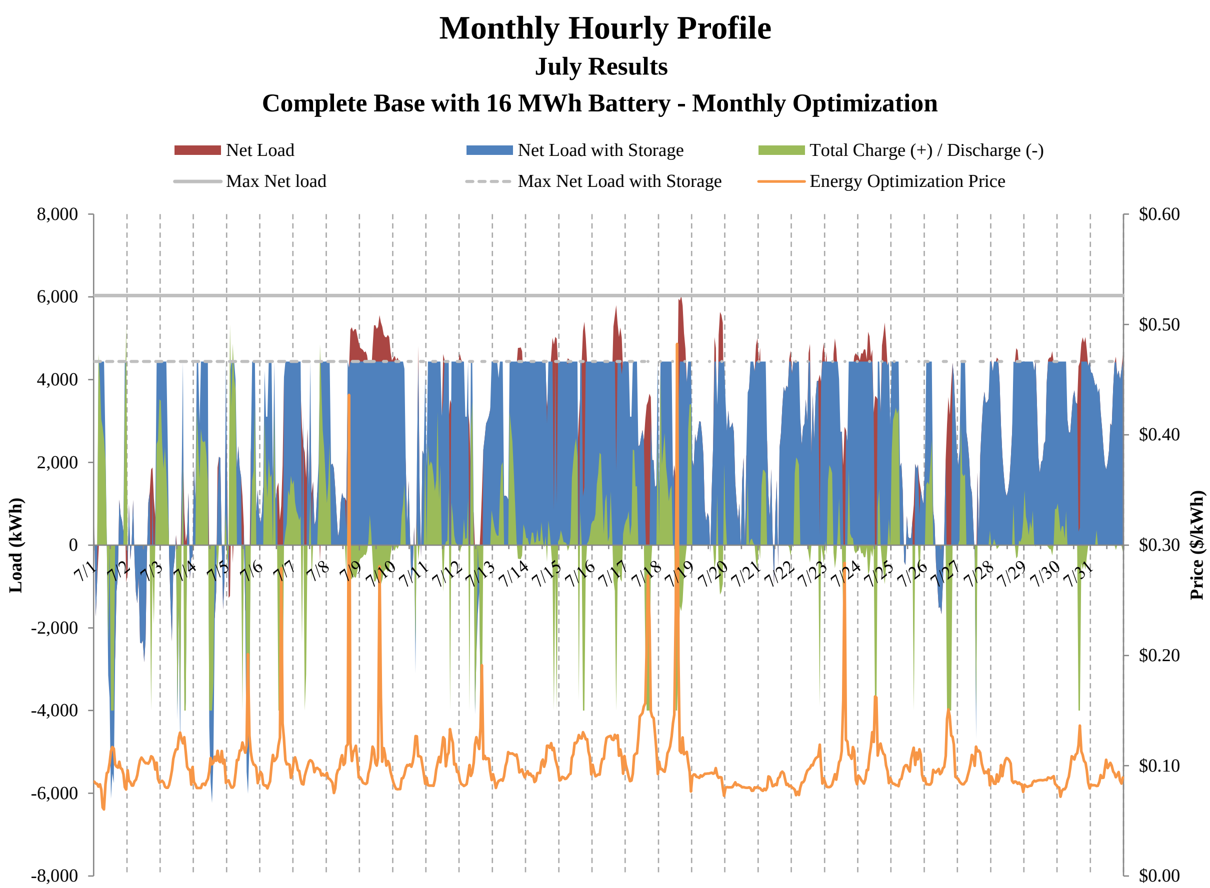
1/27
1/28
1/29
1/30
1/31

Figure C-15


Monthly Hourly Profile
July Results
Complete Base with 16 MWh Battery - Monthly Optimization
Net Load
Net Load with Storage
Total Charge (+) / Discharge (-)
Max Net load
Max Net Load with Storage
Energy Optimization Price
Load (kWh)
Price ($/kWh)
8,000
6,000
4,000
2,000
0
-2,000
-4,000
-6,000
-8,000
$0.60
$0.50
$0.40
$0.30
$0.20
$0.10
$0.00
7/1 7/2 7/3 7/4 7/5 7/6 7/7 7/8 7/9 7/10 7/11 7/12 7/13 7/14 7/15 7/16 7/17 7/18 7/19 7/20 7/21 7/22 7/23 7/24 7/25 7/26 7/27 7/28 7/29 7/30 7/31

4. Critical Load Analysis

Table C-7

Days with Positive Net Load

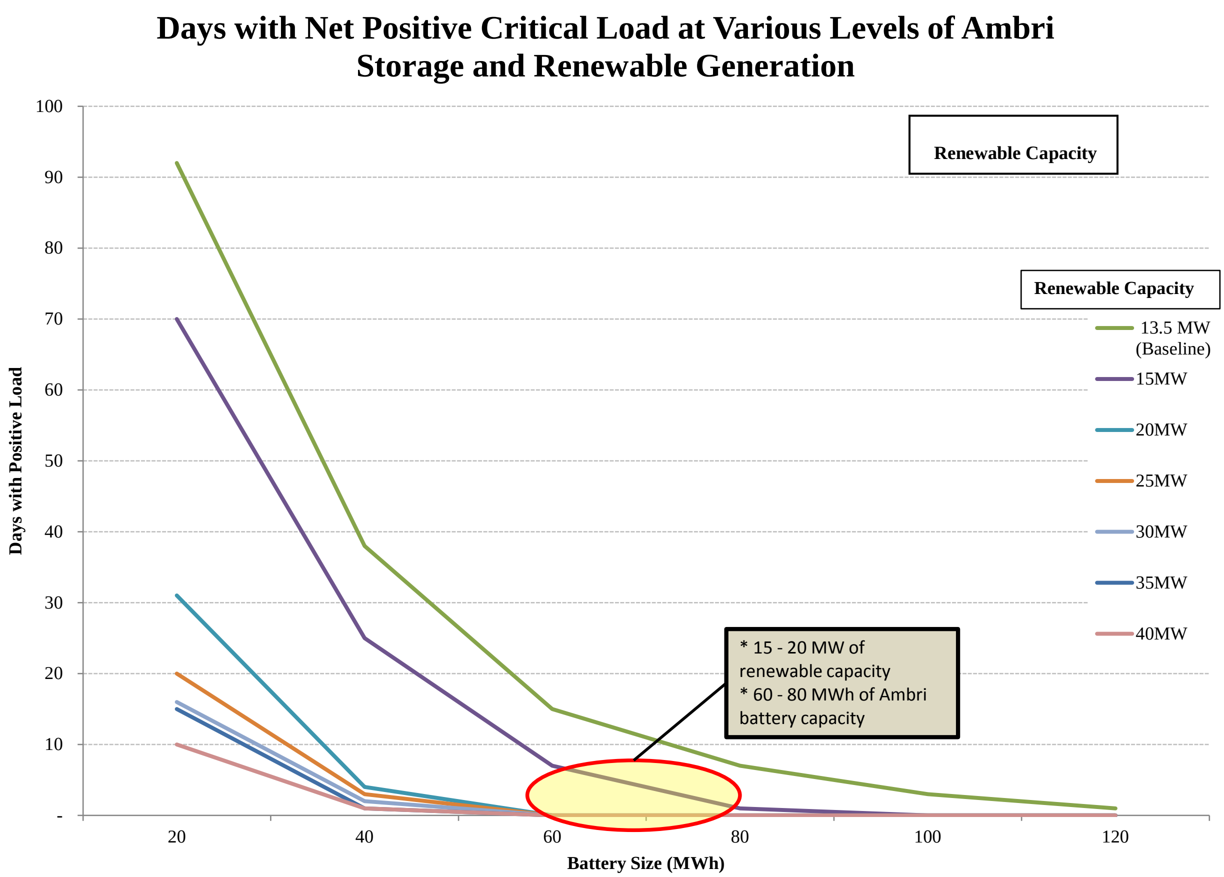
Battery Size (MWh)	Renewable Generation Capacity (MW) 13.5 MW (Baseline)	15MW	20MW	25MW	30MW	35MW	40MW
20	92	70	31	20	16	15	10
40	38	25	4	3	2	1	1
60	15	7	-	-	-	-	-
80	7	1	-	-	-	-	-
100	3	-	-	-	-	-	-
120	1	-	-	-	-	-	-

Table C-8

Hours with Positive Net Load

Battery Size (MWh)	Renewable Generation Capacity (MW) 13.5 MW (Baseline)	15MW	20MW	25MW	30MW	35MW	40MW
20	694	486	201	119	85	65	44
40	285	166	19	11	8	6	4
60	120	43	-	-	-	-	-
80	62	8	-	-	-	-	-
100	21	-	-	-	-	-	-
120	5	-	-	-	-	-	-

Figure C-16


Days with Net Positive Critical Load at Various Levels of Ambri Storage and Renewable Generation
Renewable Capacity
Renewable Capacity
13.5 MW (Baseline)
15MW
20MW
25MW
30MW
35MW
40MW
* 15 - 20 MW of renewable capacity
* 60 - 80 MWh of Ambri battery capacity
Days with Positive Load
Battery Size (MWh)
100
90
80
70
60
50
40
30
20
10
-
20
40
60
80
100
120