Optimization of Data Center Battery Storage Investments for Microgrid Cost Savings, Emissions Reduction, and Reliability Enhancement

Christopher C. Thompson, P.E., Konstantinos Oikonomou, Amir H. Etemadi, Ph.D., and Volker J. Sorger, Ph.D.
Department of Electrical and Computer Engineering
The George Washington University
Washington, D.C.
thompson@gwu.edu, konstantinos@gwu.edu, etemadi@gwu.edu, and sorger@gwu.edu

***Abstract*—This paper presents a methodology for optimizing investment in data center battery storage capacity. Utility grid managers spend significant resources towards predicting and matching available power generation capacity to demand in real time. It is therefore essential for the success of the power industry that economic dispatch, energy efficiency, and grid security be maintained as power requirements change. This is especially challenging for microgrids during periods of peak demand due to limited available capacity. Data centers possess a unique requirement for short-term battery power supply where cost savings, emissions reduction, and reliability enhancement can be achieved through investment in additional battery capacity. To maximize these benefits, an optimization methodology is presented through a case study for an existing data center and microgrid. Here we discuss a case study demonstrating the effectiveness of the proposed approach. For the selected mid-size data center our results indicate monetize monthly savings of up to ten thousand dollars and 0.5 percent reduction in loss of load probability while simultaneously reducing carbon footprints. The results of this work are directed towards large data centers at university and corporate campuses, microgrids, and military installations.**

Keywords—Data center, microgrid, peak shaving, time-of-use rates

I. INTRODUCTION

Maintaining power stability in the face of constantly changing demand remains a key challenge of utility grid management. Microgrids, while becoming more prevalent, are particularly vulnerable to instability due to limited control of power supply and demand. Independent system operators and microgrid managers actively seek options, such as energy storage, to help maintain this balance, especially during peak hours.

Data center battery storage systems have been proposed to help balance power generation and demand using a variety of methods; for instance various types of information technologies are investigated towards extending the battery lifetime [1], and smart grid technologies are integrated to optimize renewable energy and energy storage, and enhance overall system reliability [2]. Systems that use data center and electric vehicle storage systems to provide ancillary services have been proposed as well [3, 4]. Moreover, large data centers were proposed to actively influence price levels by manipulating demands, and peak shaving was applied to boost quantity of servers and reduce cost of server ownership [9, 10]. Note that most of the proposed solutions accomplish these objectives through some form of peak shaving.

This paper proposes three important elements that are underdeveloped in previous works to create a design methodology for a battery storage system. (1) Data centers and microgrids should coordinate battery installation, charging, and discharging; in fact, in this work we show that the microgrid receives sufficient financial revenue to justify the investment, independent of the benefit to the data center. (2) The proposed supplemental storage solution involves only battery and control equipment installation. All other required infrastructure, e.g., the power electronic interface, is a necessary and preexisting part of data center operation, thus minimizing total investment and allowing for a higher rate of return. (3) In this work, we propose an optimization routine that considers costs, emissions, and reliability. These objectives, when achieved, create a unique opportunity to reduce energy peaks in a profitable way, while improving back-up power capacity for tenant data centers simultaneously.

Approximately three million data centers exist in the United States consuming nearly 91 terawatt hours of energy each year, and is expected to grow to 140 terawatt hours by 2020 [7, 14]. This amounts to roughly 2% of American electricity consumption in 2013. This ratio is even more significant for the federal government, where about 10% of electricity consumption is due to data center operation [8]. Thus, improvements in this sector can have far-reaching benefits–especially for the military and federal government for whom microgrid reliability, reduced operational costs, and energy consumption savings are paramount.

II. CHALLENGE OF GRID STABILITY

While the grid stability challenge is conceptually and technologically overt, its efficient maintenance can be rather complex. Starting from first principles, the power demanded must equal power supplied at all times. The principal difficulty in maintaining grid stability is the daily fluctuation of the power demand; the larger the volatility of supply and demand, the less stable the grid becomes. While demand follows somewhat predictable patterns, unanticipated events related to weather, equipment failures, and other unplanned factors require constant attention and control by grid operators to supply the appropriate quantity of generated power at the proper locations. In periods where the demand is low, grid managers may choose from a variety of generation options to meet the demand and drive down costs that can be passed on to customers. In periods where the demand is high, grid managers have fewer choices in which generation sources to choose, such that more expensive and unreliable options must be considered to meet the peak demand, resulting in higher operational costs.

Utilities respond to this challenge by instituting time-of-use (TOU) pricing. This is a billing scheme where customers are charged based on both the quantity and time of power usage. Rates for consumption (kWh) and demand (kW) are higher during peak hours and lower during off-peak hours. While every energy utility has its own methods of billing for its customers, most institute some form of TOU pricing. One example TOU pricing scheme is shown [Fig. 1].

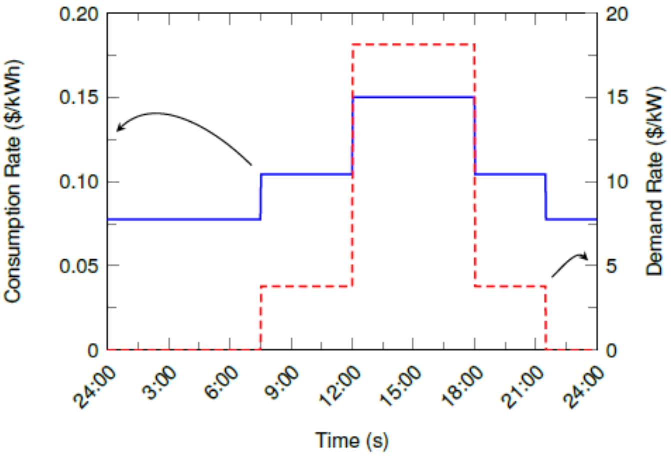

Fig. 1. Sample time-of-use utility rate structure.

This TOU rate structure (1) institutes fairness by charging customers according to their effect on the power system, and (2) acts as a financial disincentive to alter customer behavior into drawing power when it is more beneficial to the grid. Large commercial and industrial customers are almost universally billed in this way, and some states have even considered options for residential TOU billing [11]. This billing scheme offers savings opportunities if a customer can successfully shift load requirements from peak periods to off-peak periods. Savings can come from reductions in both peak consumption and peak demand charges. TOU pricing, then, by its design, creates an opportunity for energy storage to reduce burden on the power system during peak hours – if it can be made economically viable, which is a key motivation for this work.

III. OPPORTUNITY IN DATA CENTERS

The most significant inhibitor for large-scale deployment of battery storage on the grid is the cost of installation. Using data centers as a vehicle for grid storage is an intentional and important choice, largely because much of the essential infrastructure is already installed, connected, and operational; this creates an opportunity to establish a profitable rate of return on supplemental battery investment. In addition to the financial incentives, peak shaving has a direct positive effect on grid reliability and on emission reduction.

Data centers have several features that create an opportunity to improve broad grid stability. First, the information technology (IT) equipment typically consumes a very stable quantity of power that varies only slightly throughout the day and year. Second, data centers tend to consume a significant portion of microgrid load. Third, nearly all data centers contain an uninterruptible power supply (UPS) system as a back-up power option.

UPS systems are a required part of the design of a data center power system because of the equipment reliability needed for information processing. These systems are generally designed to carry the facility load for a short period of time, usually less than an hour, allowing time for the utility power to return or for a more permanent source of back-up power to come online, such as a standby generator. Essentially, a UPS is a rectifier-inverter system connected to a source of DC power that acts as a short-term emergency supply when the primary source is lost. The emergency source is most often batteries, though flywheels are sometimes used as well. Additional battery capacity can be installed without changing the power capacity (kVA/kW) of the UPS system [Fig. 2].

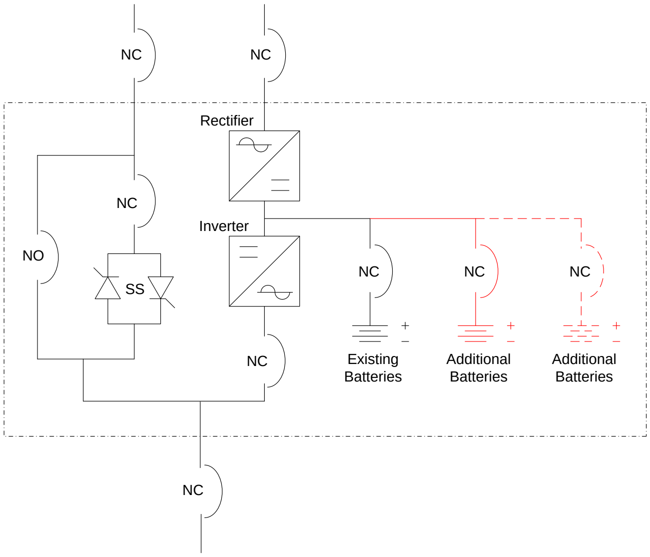

Fig. 2. Typical UPS system configuration (with supplemental battery).

These UPS units represent a significant investment in data center construction; they typically range on the order of $500 per kW of installed capacity. This is the primary reason that grid-scale battery storage is currently untenable; investment costs are so high that payback periods range beyond the service life of the UPS equipment. Because data centers must invest in the backup power equipment for operational reasons, an opportunity is created for the host microgrid to expand the battery capacity of the system, without having to purchase any of the UPS infrastructure, dropping the cost of energy storage investment per kilowatt dramatically, as analyzed in Section V.

In this process, the UPS battery capacity expansion must have minimal effects on the existing data center equipment. That is, the UPS will continue to produce AC power at the same rate as before the installation, the total quantity of daily power consumed will remain the same, and only the time of the conversion from AC to DC power is altered. Furthermore, the charging and discharging cycles affect the battery life, and depth of discharge has been taken into account to improve the accuracy of the cost estimation.

A partnership between a data center and its host microgrid improves the situation for all parties: (1) the data center gains additional, local battery capacity in the event of grid failure and (2) the grid gains the ability to shed the load of a major customer during peak hours, reducing operational costs, CO_2 production, and improving grid reliability.

As an aside, data centers often have little to gain by making large investments in storage capacity on their own. Generally, savings are realized when peak loads are reduced; because data centers have more or less constant loads, reduction of demand at one time (discharging) causes an increase in demand at another time (charging). Benefits are limited to consumption (kWh) savings. The host microgrid receives both demand and consumption savings because its load is more variable, thus, it has more peak shaving benefits.

IV. GROUND RULES FOR ADDITIONAL BATTERY STORAGE

There are a few caveats to this investment strategy. Cost trends, available technologies, relationships between data centers and power providers, shape of load profiles, and utility rate structures all make a difference to whether a battery installation plan will be productive. Many of the finer details will be worked out in the design phase of a battery installation.

Several prerequisites are necessary to create a working partnership between the microgrid and the data center.

- The opportunity for beneficial battery installation stems from the data center being a portion of a larger customer load – where the larger customer is paying the utility bill. This is common for large corporate and university campuses as well as on military installations. In the case of a microgrid, this is incentivized, due to the need for control and reliability maximization when operating in the islanded (i.e. off-grid) mode.
- The data center should represent a significant portion of the total load. This could be especially important in a microgrid; the larger the data center load is relative to the total microgrid load, the more control the grid manager will have over the total load.
- A formal agreement should establish the operating conditions. This should state the expected frequency and duration of typical charge and discharge events, the maximum depth-of-discharge of the batteries (i.e. minimum remaining charge required at all times) and special circumstances when power will not be interrupted, such as preceding thunderstorms or planned maintenance events.
- Project costs could generally be divided along the following lines. The cost of the project to the microgrid should include only the additional battery capacity and any ancillary equipment (e.g., control relays, ventilation fans, spill containment). The data center should be responsible for the UPS equipment and the minimum battery capacity required.

The quantity of battery storage purchased is dependent on the desired duration of peak shaving on the grid, the depth-of-discharge rating for the selected batteries, and the minimum storage capacity required by the data center. This should be optimized while maintaining data center requirements.

Optimizing the timing of charge and discharge can be complicated. From a cost perspective, there are several assumptions that should be made in the planning stage; during operation, these can be relaxed after installation as specific situations warrant.

- For a typical day, the total charge should be equal to the total discharge. A load curve for the grid should be projected in the model. This allows the control system to forecast the most optimal times to charge and discharge economically in a typical 24-hour period.
- The UPS system should plan to discharge once and charge once in a 24-hour period. Because of the cyclical nature of the load each day and the TOU incentives in place, this scenario is likely the case. Actual conditions may warrant multiple charges and discharges because of outages or zero activity due to anticipated maintenance or weather events. These will be the exception to normal operation.
- The UPS will either charge at full capacity, discharge at the load demand rate, or hold at current capacity. Previous works have suggested load shedding at variable rates [1, 3]; in practice this is difficult to achieve since relays and other hardware in the UPS operate with switches, placing them in on and off states. Reducing loads to variable, partial quantities requires significant hardware and/or software investments.

This scheme is advantageous only in jurisdictions where TOU is already implemented. The more significant the TOU billing incentive, the greater economic benefit can be realized (reliability and emissions benefits can be realized in all cases regardless of the billing scheme).

V. CASE STUDIES

This section presents the results of numerical case studies. Battery optimal sizing, its impact on system reliability and the environment are discussed. Moreover, a sensitivity analysis is presented where the optimal size of battery as a function of its cost of installation and amount of data center demand is determined.

A. Optimal Battery Sizing for Cost Reductions

The supplemental battery installation must be carefully designed, where two key factors should be optimized to enable profitability: (1) the quantity of battery capacity and (2) the ideal charge and discharge times as a function of the load profile. Note that the electrical load data used in the following case is real field data for an existing data center located on an operational microgrid [Fig. 3].

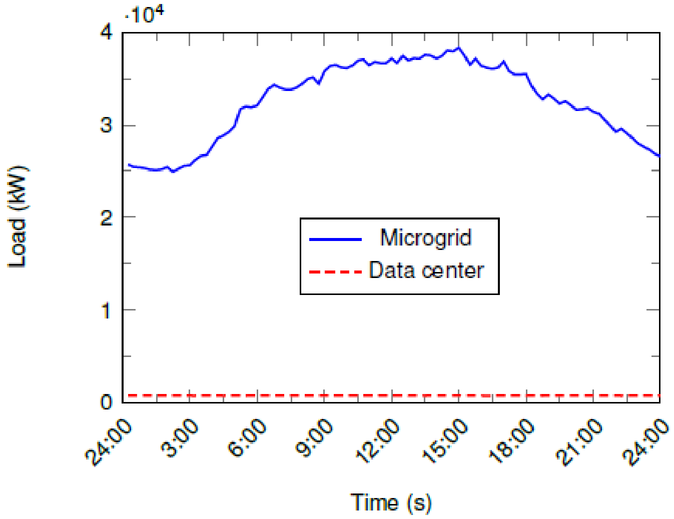

Fig. 3. Peak summer microgrid and data center load profiles.

The methodology for optimizing the battery system is a two-step process that uses data center and microgrid load profiles, applicable utility rates, battery data–installation costs, and expected life ratings as a function of depth-of-discharge.

Step 1: Representative microgrid and data center load profiles are divided into discrete segments that correspond to the utility rate structure, typically 15-minute increments. Each segment has an associated cost that is a function of the power demand and utility rates at that time. Discharging or charging the batteries during these periods changes that cost by a calculable amount. These potential changes in cost are ranked to establish a list of the preferred charge and discharge opportunities throughout the day. The quantity of available battery capacity (kWh) determines the number of opportunities that the system can execute. The formulas that follow apply to the optimization routine for the rate structure shown in Fig. 1; adjustments are required for other TOU rates. The total monthly savings, as a result of battery capacity expansion, is given by

$$S = \sum_{n=1}^{d} (P_{max,n} - P_{max,n+1})^{*} R_{d,n} + 30\mathrm{P}_{\mathrm{dc,n}} t\, R_{c,n} \qquad (1)$$

where

S is the total amount of monthly savings

$\mathrm{P}_{\mathrm{dc,n}}$ is power drawn by the data center at the nth time segment

$P_{max,n}$ is the nth highest power demand of the microgrid. $P_{max,n} - P_{max,n+1}$ must be less than or equal to data center power, $P_{dc,n}$

$R_{d,n}$ is the demand (kW) cost rate at the nth time segment.

t is the time segment duration in hours.

$R_{c,n}$ is the consumption (kWh) cost rate at the nth segment.

d is the number of discharging opportunities per day. For systems with constant data center demand:

$$d = \frac{\mathrm{Charge_{max}} - \mathrm{Charge_{min}}}{t \times P_{dc,ave}} \qquad (2)$$

$\mathrm{Charge_{min}}$ is the minimum installed charge capacity (kWh) the data center will accept, and is typically already installed in the system.

$\mathrm{Charge_{max}}$ is the maximum installed charge capacity (kWh)

The total monthly economic losses as a result of battery capacity expansion is given by

$$L = \sum_{k=1}^{c} (P_{UPS} - P_{dc,k}) R_{d,k} + 30(P_{UPS} - P_{dc,k}) t\, R_{c,k} + B \qquad (3)$$

where

L is the total monthly losses.

P_{UPS} is the maximum charge rate of the UPS.

$R_{d,k}$ is the demand (kW) cost rate at the kth time segment.

$R_{c,k}$ is the consumption (kWh) cost rate at the kth segment.

c is the number of charging opportunities per day. For systems with constant data center demand:

$$c = \frac{\mathrm{Charge}_{max} - \mathrm{Charge_{min}}}{t \times (P_{\mathrm{dc,charge}} - P_{\mathrm{dc,ave}})} \qquad (4)$$

B is the monthly cost of the batteries. Battery investment costs are divided over life of the battery:

$$B = \frac{(\mathrm{Charge_{max}} - \mathrm{Charge_{min}}) B_{cost}}{B_{life}} \qquad (5)$$

B_{cost} is the cost of the battery installation in $/kWh.

B_{life} is the rated life of the battery in cycles at the system depth-of-discharge (DoD):

$$\mathrm{DoD} = 1 - \frac{\mathrm{Charge_{min}}}{\mathrm{Charge_{max}}} \qquad (6)$$

Step 2: Using the existing data center battery capacity as the minimum acceptable charge, incremental quantities of battery capacity are added –notionally– and the difference in energy costs are calculated. Savings result from reductions in demand and consumption during peak periods (discharging). Losses result from increases in consumption during off-peak hours (charging) and from battery installation costs. It is possible that demand charges would increase during off-peak hours, but rate structures and load profiles usually prevent this. Fig. 4 shows the savings and losses associated with discharging and charging activity as quantity of battery capacity increases.

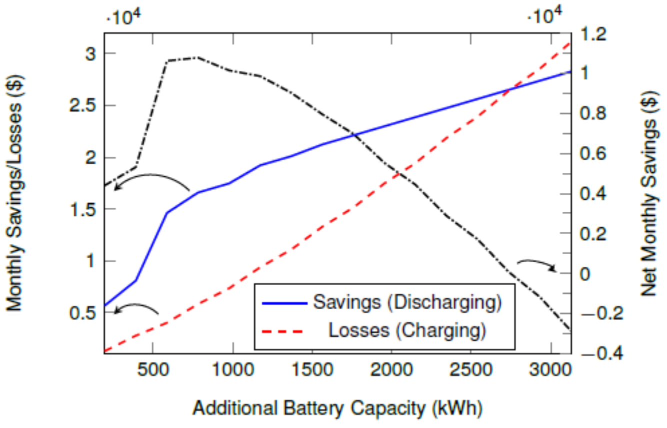

Fig. 4. Monthly savings (due to discharging) and losses (due to charging) and their difference as a function of additional battery.

In Fig. 4, the point where the loss curve intersects the savings curve is important because it represents the maximum amount of battery capacity that can be profitably installed. In order to maximize profits, the microgrid and data center should install the amount of battery where the difference between the savings curve and the losses curve is the greatest. The net savings is therefore the difference between both trend lines.

Our results show that the optimal amount of battery storage to maximize profit is about 800 kWh, at a battery installation cost of $350 per kWh. The maximum capacity that can be profitably installed is approximately 2,800 kWh for the same battery installation cost. The depth-of-discharge, of the batteries increases as more energy storage is introduced to the system (i.e. amount of energy discharged is a greater and greater fraction of total storage capacity). This has a logarithmic effect on battery life; the cost model takes this into account [15]. Depth-of-discharge ratings for many types of batteries are also often limited to 0.8 because the logarithmic effect becomes more pronounced; this places a functional limit for supplemental storage capacity of five times the minimum acceptable charge.

B. Environmental Effects

The amount of battery storage employed has an effect on the emission of CO_2 and other pollutants. The strategy for evaluating the effect of battery storage is similar to Step 1 of the cost optimization routine. Each of the evaluated time segments results in a quantity of kWh that is consumed. During peak periods, CO_2 production is higher than during off-peak periods due to the types of power generation used at these times [6]. The difference in production rates is multiplied by the change in power consumption to yield a quantity of CO_2 produced as a function of additional battery capacity employed [Fig. 5].

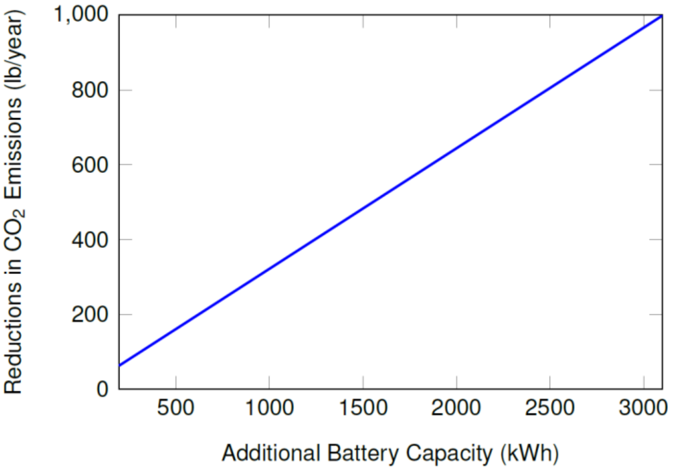

Fig. 5. Emissions reduction for varying battery capacities.

The reduction in CO_2 will gradually become negligible as the peak load discharging opportunities are all exchanged for off-peak charging opportunities through battery activity. Note that a cap and trade system could translate this effect into dollars, for certain power markets, a topic which will be explored in future works.

C. Reliability Enhancement

Changes in microgrid load, due to data center charging and discharging activity, have an effect on the reliability of the microgrid. Reliability is a function of system design, equipment failure rates, availability of power sources, and system load [13]. Keeping other system variables constant, reductions in load result in higher reliability, and vice versa. However, as the load changes throughout the day, so do the available power sources. For instance, at peak hours, solar power is available to the grid, albeit in limited quantity. The following analysis of the effect on reliability must then reflect both quantity of storage available and the time of daily charge and discharge activity.

To evaluate the system reliability, the system power sources and loads are modeled using the probabilistic Monte Carlo method in the DigSILENT software package [16]. The microgrid peak demand decreases as battery capacity increases; these varying demand profiles were taken into account in this case study. Several types of power sources were selected to correspond with those in the actual microgrid.

The input data for the model included availability and capacity outage probability tables (COPT) for the four types of power sources located on the microgrid. In the model, operational availability for the conventional generation sources (diesel and natural gas) is 0.9 [23]. COPT information for the wind and solar contribution is shown in Table I [23].

TABLE I. COPT FOR RENEWABLE ENERGY CONTRIBUTORS

Solar		**Wind**	
Power Output (kW)	***Probability (%)***	***Power Output (kW)***	***Probability (%)***
200	0	300	2
180	1	270	5
160	4	240	3
140	5	210	4
120	4	180	6
100	4	150	8
80	5	120	9
60	6	90	9
40	8	60	13
20	12	30	11
0	52	0	31

To perform the analysis, the study period is divided into segments where the operating state for each power source is selected by a random number generator [12]. This is compared with the load profile and repeated until the following two system adequacy indices converge: the loss of load probability (LOLP), which is the probability that some amount of load is lost during the course of the day [12], and the energy demand not supplied (EDNS), which is given by the average value of the power demand that cannot be provided when there is a loss of load [12]. LOLP tends to be highest when the load-to-source ratio is maximized. Both LOLP and EDNS vary with battery capacity [Fig. 6].

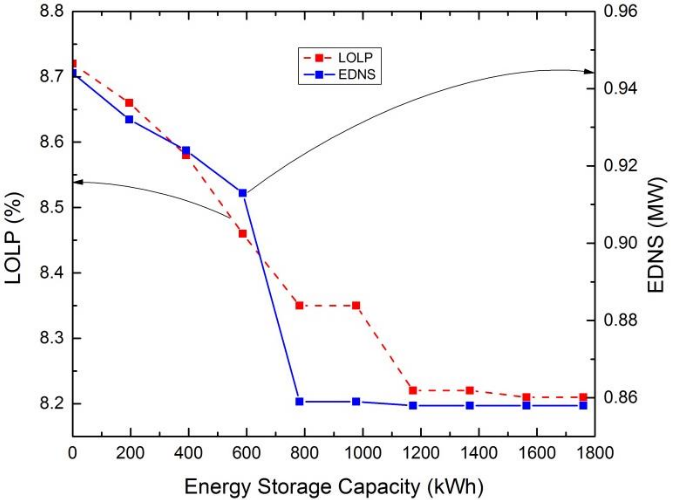

Fig. 6. LOLP and EDNS for varying battery capacities.

Our results show that both LOLP and EDNS are asymptotic to minimum values established by microgrid and data center demand characteristics. As battery capacity increases, microgrid demand is reduced until the total reduction equals the magnitude of the data center demand. At that point, further investments in supplemental batteries have a negligible effect on reliability.

In addition to the reliability benefits provided to the microgrid, the data center itself has a higher battery capacity for a majority of the day, which increases the emergency power reserve for a power outage [Fig. 7].

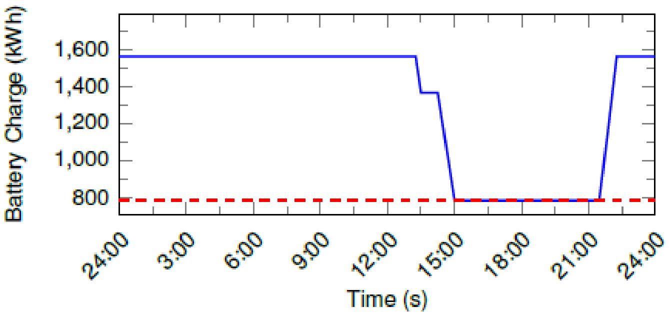

Fig. 7. Battery charge for original (dashed) and upgraded (solid) systems.

During most of the peak period, the battery charge is at the minimum acceptable charge value (the same capacity it had before the upgrades). For the rest of the 24 hour period, the available charge is double what it was originally, leading to twice the emergency response time for the data center.

D. Sensitivity Analysis: Cost of Battery and Data Center Demand

The viability of installing supplemental battery capacity in in data center facilities is sensitive to a number of variables. Understanding how these variables affect the financial aspect of the installation is critical to determining whether the investment will be profitable. Cost of battery installation ($/kWh) and data center demand (kW) are the two main factors that have a significant effect on the profitability of the investment [Fig. 8].

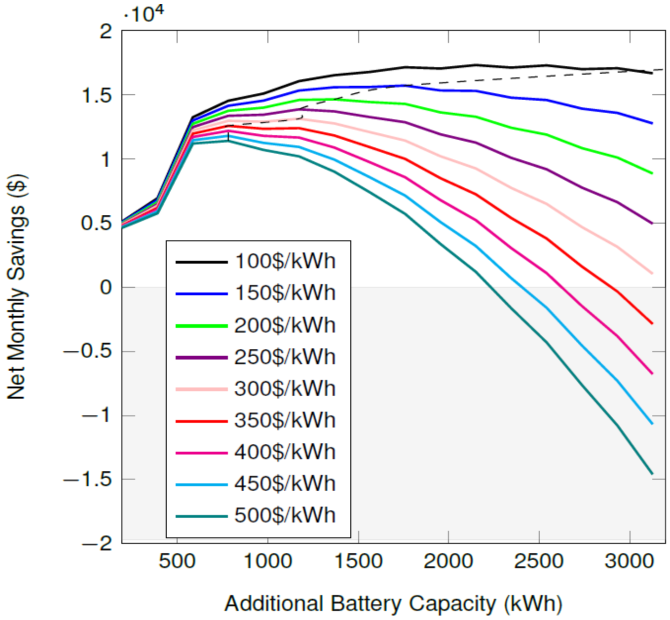

Figure 8: Net monthly savings curves for varying battery cost.

Battery costs have experienced and continue to experience reductions in price. Projections for installation costs over the next seven to eight years show a drop to $230 per kWh [5]. This increases the profitability of battery installation systems dramatically, allowing for larger and larger quantities to be installed, affecting business revenue, grid reliability, and emission rates positively.

Increasing data center demand reduces cost savings potential for the presented case [Fig. 9]. This is highly dependent on battery cost. At $350/kWh of installed battery capacity, the curves are dominated by battery expense, which acts as a bias against large systems. As battery costs decline, the right side of the curves increase, which favors systems capable of installing larger battery capacity.

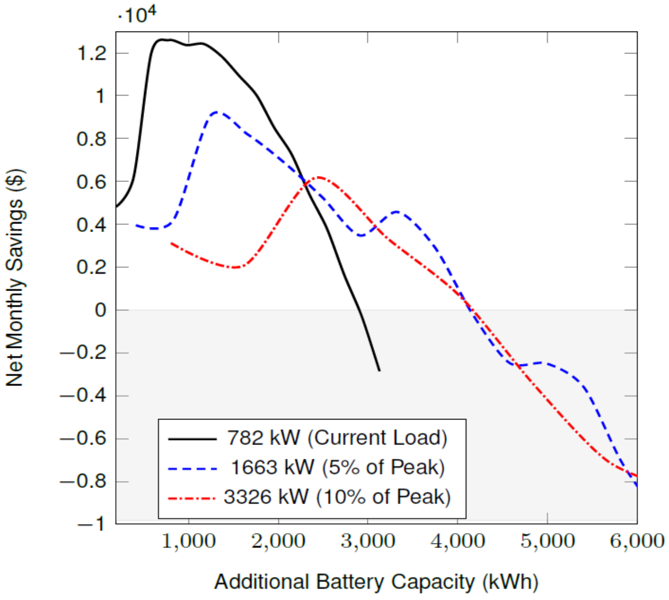

Fig. 9. Net monthly savings curves for varying data center demand.

However, if the objective is to minimize emissions rather than cost, for example, the optimum operating point without financial losses (i.e. where net monthly savings equals zero) would occur at 2,800 kWh of battery capacity for the current system and 4,100 kWh for each of the larger data centers considered. The extra storage capacity installed on either of the larger systems would result in further emissions reduction of 395 pounds of CO_2 per year.

Battery installation is also sensitive to utility prices; while most utilities have a TOU rate structure in place, aggressive rate structures (i.e. those that have large price differences between peak and off-peak charges) affect battery investment profitability more strongly. As battery prices continue to drop, these regions will likely be first to see the effect.

VI. CONCLUSION

This work combines several ideas to create an energy storage solution with advantageous practical implications. Data centers and microgrids are growing in prevalence; linking their resources and requirements together helps improve operations in both. Here we present a method that supports an investment and design decision in an optimized and measurable way. Our results show that there is an optimal point at which cost savings are maximized. This places emphasis on the importance on sizing battery capacity appropriately; installing too much yields financial losses and negligible effect to reliability enhancement. The results also show that these systems are sensitive to battery installation costs, pointing to higher future rates of return if battery price trends continue. If these systems can be designed and installed in a financially prudent and mutually beneficial manner, data center battery storage could become a bridge between where we are now and full-scale grid-level implementation of battery storage technology.

REFERENCES

[1] B. Aksanli, T. Rosing, and E. Pettis, "Architecting Efficient Peak Power Shaving Using Batteries in Data Centers," 21st IEEE International Symposium on Modeling, Analysis & Simulation of Computer and Telecommunication Systems (MASCOTS), pp. 14-16, Aug. 2013.

[2] Y. Xu and C. Singh, "Power System Reliability Impact of Energy Storage Integration with Intelligent Operation Strategy," IEEE Transactions on Smart Grid, VOL. 5, NO. 2, MARCH 2014 pp.1129-1137.

[3] M. Brocanelli, S. Li, X. Wang, and W. Zhang, "Joint Management of Data Centers and Electric Vehicles for Maximized Regulation Profits," IEEE, 2013, pp. 1-10.

[4] B. Aksanli and T. Rosing, "Providing Regulation Services and Managing Data Center Peak Power Budgets," IEEE, 2014.

[5] J. Kosowatz, "Batteries for Managing the Grid," Mechanical Engineering, ASME, March 2015.

[6] eGRID, "eGRID 9th edition version 1.0 Year 2010 GHG Annual Output Emission Rates," EPA, 2010, http://www.epa.gov/egrid.

[7] Natural Resources Defense Council, "America's Data Centers Consuming and Wasting Growing Amounts of Energy," February 2015. http://www.nrdc.org/energy/data-center-efficiency-assessment.asp

[8] M. Vargas, "10 Facts to Know About Data Centers," EERE. November 2015. http://energy.gov/eere/articles/10-facts-know-about-data-centers

[9] J. Yao, X. Liu, W. He, A. Rahman, "Dynamic Control of Electricity Cost with Power Demand Smoothing and Peak Shaving for Distributed Internet Data Centers," 2012 32nd IEEE International Conference on Distributed Computing Systems, pp.416-424.

[10] V. Kontorinis, L. Zhang, B. Aksanli, J. Sampson, H. Homayoun, E. Pettis, D. Tullsen, T. Rosing, "Managing Distributed UPS Energy for Effective Power Capping in Data Centers," IEEE, 2012, pp. 488-499.

[11] Senate Bill No. 1090, Chapter 625 "An act to amend Section 745 of the Public Utilities Code, relating to electricity." September 2014. http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1090

[12] Markus Pöller, "Monte Carlo Simulation for Generation Adequacy Simulations," PowerFactory User's Group Meeting 2011 and DIgSILENT Pacific 10th Anniversery, Melbourne February 24-26, 2011.

[13] Pedram Jahangiri and Mahmud Fotuhi–Firuzabad, "Reliability Assessment of Distribution System with Distributed Generation," second IEEE International Conference on Power and Energy (PECon 08), December 1-3, 2008.

[14] "Report to Congress on Server and Data Center Energy Efficiency," U.S. EPA Energy Star Program, pp. 17-18, August 2, 2007.

[15] S. Drouilhet, B.L.Johnson, "A Battery Life Prediction Method for Hybrid Power Applications," NREL, p. 18, January, 1997.

[16] http://www.digsilent.de/index.php/products-powerfactory.html

[17] Power System Test Case Archive, IEEE reliability test system: 1996, https://www.ee.washington.edu/research/pstca/rts/pg_tcarts.htm.

[18] Barker, P.P.; De Mello, R.W., "Determining the impact of distributed generation on power Systems". I. Radial distribution systems", Power Engineering Society Summer Meeting, 2000. IEEE, Volume: 3, 2000, Page(s): 1645 -1656 vol. 3.

[19] IEEE Distribution Planning Working Group Report, "Radial distribution test feeders", IEEE Transactioins on Power Systems,, August 1991, Volume 6, Number 3, pp 975-985.

[20] L. Yu, T. Jiang, andY. Cao, "Energy Cost Minimization for Distributed Internet Data Centers in Smart Microgrids Considering Power Outages," IEEE Transactions on Parallel and Distributed Systems, VOL. 26, NO. 1, JANUARY 2015, pp. 120-130.

[21] Y. Guo, Y. Fang, "Electricity Cost Saving Strategy in Data Centers by Using Energy Storage," IEEE Transactions on Parallel and Distributed Systems, VOL. 24, NO. 6, JUNE 2013, pp. 1149-1160.

[22] Survey of Reliability and Availability Information for Power Distribution, Power Generation, and Heating, Ventilating and Air Conditioning (HVAC) Components for Commercial, Industrial, and Utility Installations, U.S. Army Technical Manaul, 22 July 2006.

[23] J. Choi, J. Park, K. Cho, M. Shahihdehpour, and R. Billington, "Grid Constrained Probabilistic Reliability Evaluation of Power Systems Including Wind Turbine Generator", 978-1-4244-6551-4/10,IEEE 2010