PNNL-30656

American-Made Challenges Round 2 Voucher: Orison Enables Solar

Project Report

November 2020

Andrew P Reiman
Ankit Singhal
Allison M Campbell

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

Orison, a behind-the-meter (BTM) energy storage company was awarded a competitive voucher for technical assistance from a national laboratory through the United States Department of Energy Solar Energy Technologies Office program: American-Made Solar Prize. This report documents the technical assistance provided by Pacific Northwest National Laboratory (PNNL) to Orison as part of the American-Made Challenges Round 2 Voucher: Orison Enables Solar project.

PNNL developed a testbed and used it to demonstrate, using modeling and simulation, the capability of controlled BTM energy storage to (1) reduce net load variability caused by appliances and distributed generation and (2) enable customers to respond to time-of-use pricing. The testbed demonstrates the effects of temporally diverse disaggregated residential loads by modeling the interaction between four elements at one-minute resolution: BTM storage, BTM photovoltaic systems, high-fidelity customer loads, and the distribution secondary transformer. Considerations for a future multi-objective controller are also discussed.

We show that load leveling can shave peak loads or limit solar photovoltaic export and that load shifting enables customers to reduce load during “peak” pricing intervals. In simulations, load leveling was effective up to the charging and discharging limits of the storage systems and the effectiveness of load shifting was a function of the energy capacity of the storage systems. These results demonstrate that controlled BTM storage can positively affect both sides of the meter. Furthermore, the results may assist BTM storage vendors aiming to balance storage and inverter capacity and to define revenue-maximizing controls algorithms.

Acknowledgments

This report was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy.

Acronyms and Abbreviations

BTM	behind-the-meter
DR-SES	Demand Response-Solar Energy System
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation
HVAC	heating, ventilation, and air conditioning
NEM	Net Energy Metering
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
SOC	state-of-charge
TMY	typical meteorological year
TOU	time-of-use

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1.0 Introduction

The American-Made Challenges Round 2 Voucher: Orison Enables Solar project was conducted to provide technical assistance to Orison, a behind-the-meter (BTM) storage company. Orison was a Round 2 Solar Prize Set! contest winner under the Solar Prize's voucher program which is managed by National Renewable Energy Laboratory.

Pacific Northwest National Laboratory (PNNL) provided technical assistance under the voucher and developed a testbed that models the interaction between BTM storage and photovoltaic (PV) systems, high-fidelity customer loads and the distribution secondary at 1-minute resolution, capturing the effect of temporally diverse disaggregated residential loads.

The testbed, described in Section 2.0, is composed of a co-simulation between a grid model and a behind-the-meter (BTM) energy storage system controller. The grid model includes a simplified equivalent grid, a split-phase distribution transformer, secondary conductors, and individual residential customers. Each residential customer load is modeled independently and includes explicit representation of some appliances. Each residential customer is also modeled with a BTM solar PV system and a BTM storage system.

Simulations of the testbed without BTM storage are compared to simulations with BTM storage using two control regimes. These simulations show how the BTM storage can (1) reduce grid impacts caused by load variability and (2) enable customers to respond more effectively to time-of-use (TOU) pricing. The results demonstrate that controlled BTM storage can produce local beneficial impacts on both sides of the meter, especially where BTM PV is present.

Section 2.0 of this report describes the testbed and its components. Section 3.0 details the simulated scenarios and their results. Section 4.0 includes a brief discussion of observations and conclusions from the simulated scenarios.

2.0 Testbed

The purpose of this testbed is to enable the analysis of the impact of controlled BTM storage on load and voltage variability at the customer (distribution secondary) level. Therefore, we used a co-simulation testbed architecture that connects a distribution modeling platform, GridLAB-D, with controller modules in Python via HELICS as shown in Figure 1. GridLAB-D is a PNNL developed electric distribution system modeling and simulation tool with the capability to model end-use loads.[1] HELICS is an open-source co-simulation framework used to integrate separate simulation tools.[2] In this study, GridLAB-D sends the state-of-charge (SOC) of the storage unit and the net load consumption of the house (net meter reading) to the corresponding controller. In return, each controller sends the desired real power charging or discharging setpoint to the BTM storage system in GridLAB-D. This exchange of variables occurs every 15 seconds and is managed by the HELICS.

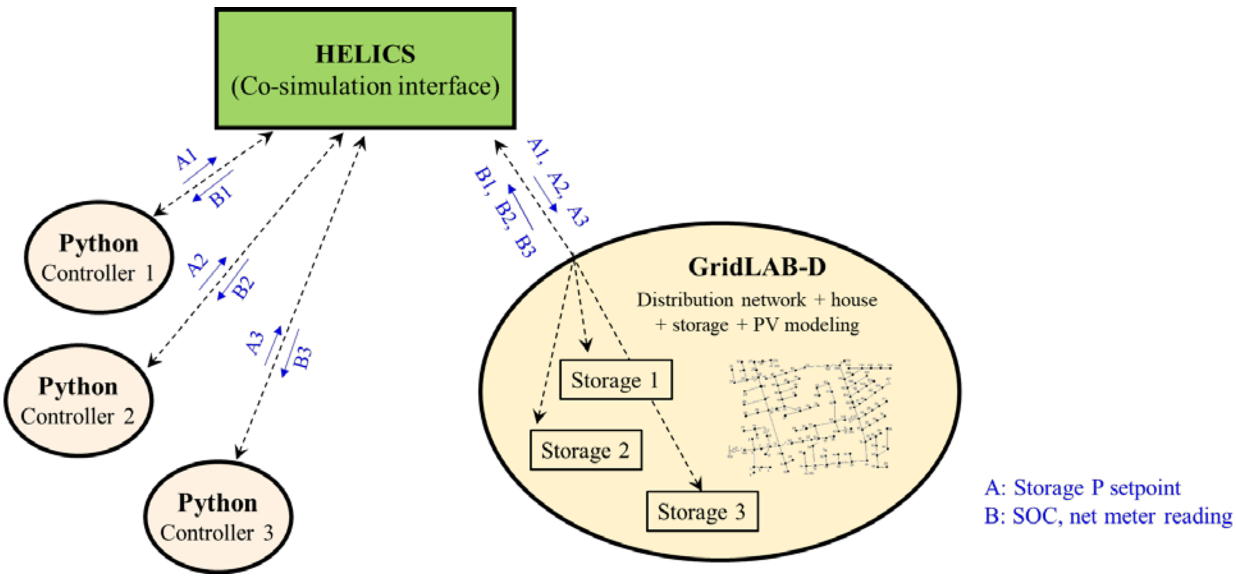

Figure 1. Co-simulation testbed modeling a distribution system with detailed houses and controlled BTM storage.

This testbed models a feeder with detail in one distribution secondary including a high-fidelity representation of ten residential customers as shown in Figure 2.

[1] https://www.gridlabd.org/
[2] https://www.helics.org/

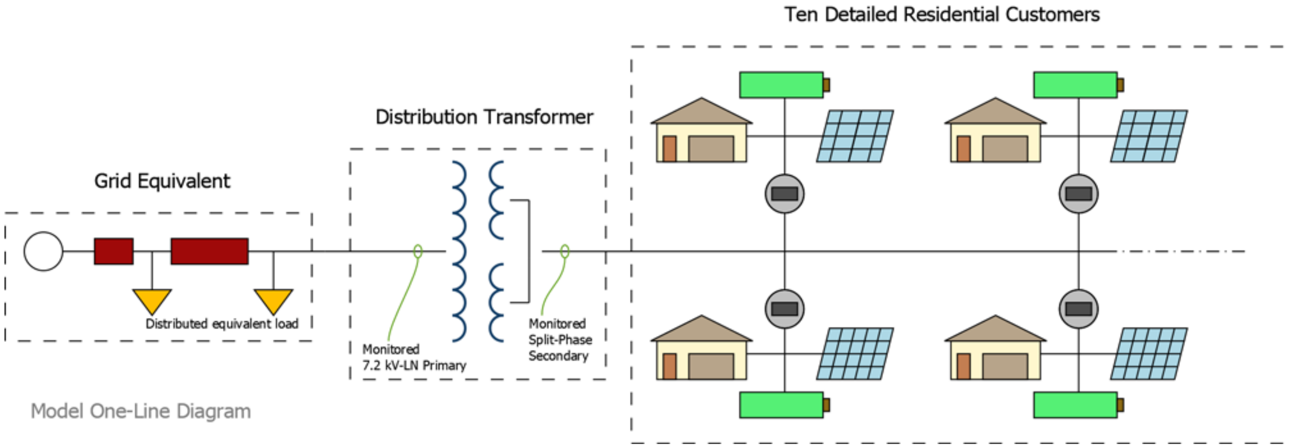

Figure 2. One-line diagram of a distribution feeder with detailed secondary and residential customer models.

The specifications and configurations of some components are described below. Additional detail can be found in the GridLAB-D documentation.

2.1 Grid Modeling

Modeling of the elements of a distribution grid is discussed below.

2.1.1 Grid Equivalent

The primary side of the feeder is modeled as a Thevenin equivalent circuit derived at the location of a randomly selected distribution transformer in “Ckt 5,”[3] an EPRI (Electric Power Research Institute) example distribution circuit. The equivalent feeder load of around 2.3 MW is modeled as a distributed load between the feeder source and distribution transformer using the method described by Kersting.[4]

2.1.2 Distribution Transformer

A single-phase center tapped “split-phase” distribution transformer is modeled with primary and secondary voltage ratings of 7.2 kV and 240 volts respectively. The rating of the transformer is 100 kVA with resistance and reactance of 0.5% and 3.9%, respectively.

2.1.3 Line Configuration and Length

The overhead triplex line (service conductor) configuration is shown in Figure 3. The red circle in the diagram represents the distribution transformer and the conductor lengths to houses are estimated assuming 110 ft. by 80 ft. lot for each house. The specifications of a 2/0 all aluminum conductor cable are used to model a triplex line configuration and are provided in Table 1.[5]

[3] http://svn.code.sf.net/p/electricdss/code/trunk/Distrib/EPRITestCircuits/
[4] W.H. Kersting, Distribution System Modeling and Analysis, Fourth Edition. CRC Press, 2017
[5] Aluminum Electrical Conductor Handbook. Aluminum Association, 1989.

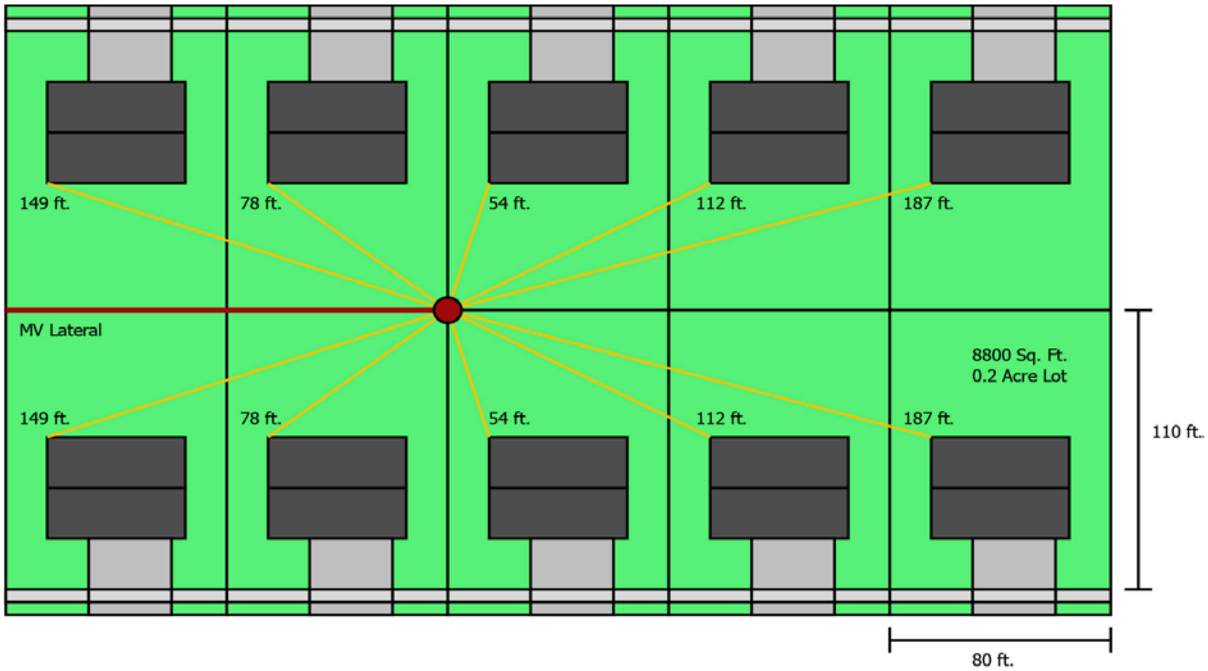

Figure 3. Overhead triplex line configuration for 10 residential customers from a distribution transformer.

Table 1. Specifications of a 2/0 all aluminum conductor cable to be used as triplex line conductor.

Property	Value
Diameter	0.420 inches
Insulation thickness	0.060 inches
Resistance	0.700 ohms/mile
Geometric mean radius	feet

2.2 Residential Customer Modeling

As represented in Figure 2, each residential customer consists of a house load, a PV system, and a BTM storage system. The house load model is composed of three load types: heating, ventilation, and air conditioning (HVAC) load, water-heater load, and end-use loads. All these loads, the PV system, and the storage system are installed behind a triplex meter at each house. The loads, PV system, and storage system are described below.

2.2.1 House and HVAC

The thermal response of the house is modeled as an equivalent thermal parameter model by GridLAB-D. The equivalent thermal parameter model captures the heat gains and losses and the effects of thermal mass as a function of weather (temperature and solar radiation), occupant behavior (thermostat settings and internal heat gains from appliances), and heating/cooling system efficiencies. Some of the thermal parameters are diversified by sampling from a uniform distribution as shown in Table 2. Weather data such as outdoor air temperature, humidity, and solar irradiance are taken from a typical metrological year (TMY3) data file for San Diego, CA. TMY3 data files contain one year of hourly data intended to represent the median weather conditions over a multiyear period.[6]

Table 2. House thermal properties and HVAC settings distribution range.

Property	Sampled distribution range
Cooling setpoint	72 – 76 deg F
Floor area	1750-3000 ft^2
Cooling coefficient of performance	3 – 3.5

2.2.2 Water Heater

Similar to a house thermal model, a dedicated water-heater model is used in GridLAB-D. Various water heater properties sampled from a uniform distribution as shown in Table 3.

Table 3. House water-heater properties and settings distribution range.

Property	Distribution range
Tank setpoint	125 – 135 deg F
Tank UA	2.75 – 3.25 btu
Tank Volume	23 – 45 gallons
Tank height	3 – 4 feet

2.2.3 End-use Loads

We used residential building stock assessment data made accessible by Northwest Energy Efficiency Alliance to model end-use loads.[7] The data set is comprised of sub-metered loads measured at 15-minute intervals. We paired an aggregated end-use loadshape with each house in the testbed. The loadshapes were aggregated by adding all the sub-metered loads beneath one residential meter except the HVAC and water heater.

2.2.4 Solar

The solar model in GridLAB-D uses panel specifications and the solar irradiance and temperature parameters from a TMY3 weather file to generate direct current power. An inverter converts the direct current power to alternating current and interfaces with the grid. A 5-kW PV system is installed at each of the houses. The inverter size is modeled as 1.05 times the PV system rating.

2.2.5 Storage

In this testbed, BTM storage systems are composed of energy storage units. Each unit includes one 1.8 kVA inverters and one or more 2.2 kWh battery modules. Each unit has a discharge

[6] https://nsrdb.nrel.gov/about/tmy.html

[7] "RBSA End Use Load Shape Data Year 2 (5 of 5)," *Northwest Energy Efficiency Alliance (NEEA)*. https://neea.org/resources/rbsa-end-use-load-shape-data-year-1-5-of-5.

power limit of 1.8 kW (inverter limited); the charge power limit is 1.8 kW (inverter limited) for multi-battery-module units and 1.0 kW (battery limited) for single-battery-module units. The maximum and minimum SOC of each storage unit is considered as 100% and 20%, respectively. Each house is allocated a number of inverters and battery based on their daily load consumption (see Table 4). The controller for each storage system is modeled in a Python agent.

Table 4. Storage units' details installed at each house.

	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8	House 9	House 10
Inverters	2	2	1	2	3	2	2	1	3	3
Battery modules	5	5	4	5	6	5	4	4	5	5
Total storage capacity (kWh)	11	11	8.8	11	13.2	11	8.8	8.8	11	11

3.0 Simulations

This section presents two control algorithms for dynamic residential battery operation. The first, Load Leveling, aims to minimize peaks and troughs in the load signal in order to reduce net load and voltage variability. The second, Load Shifting, instructs the batteries to reduce the cost to the customer through responsiveness to tiered electricity pricing. The 10 houses modeled in this analysis represent varied usage throughout a day (Figure 4, left) with solar production at each house (Figure 4, right). Throughout the simulation descriptions, houses retain the same color scheme as in Figure 5.

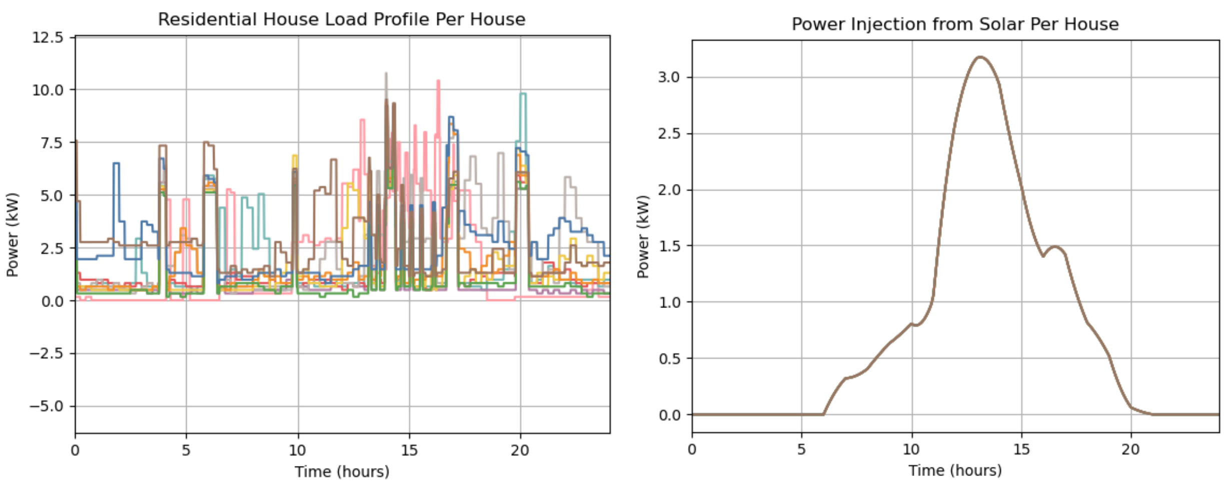

Figure 4. Residential load profiles (left) and solar power produced by each house (right).

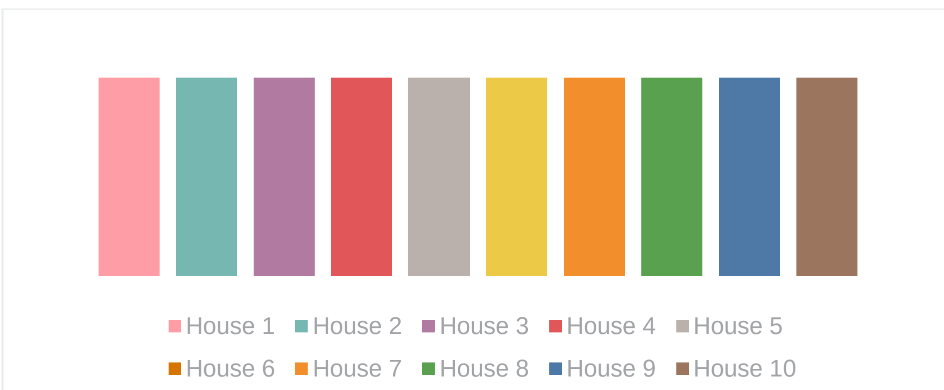

Figure 5. Color codes for residential houses.

The simulated maximum and average daily load values for each house are given in Figure 5. The ten houses in the analysis have average daily load of roughly 2 kW, and average maximum load of roughly 8 kW.

Table 5. Load details for each house.

Daily Load (kW)	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8	House 9	House 10
Maximum	10.42	9.80	8.27	8.57	10.77	8.39	9.37	8.27	9.23	9.52
Average	1.76	1.78	1.14	1.52	2.47	1.76	1.83	1.16	2.73	2.78

3.1 Scenario 1: Load Leveling

Load leveling is the process of reducing peaks and/or troughs in load power. A leveled load contributes less to system voltage variability while drawing less peak power (reducing congestion), and/or exporting less power (e.g., solar PV generation). Load leveling need not produce a constant, flat net load in order to have a positive effect on the local distribution system. BTM storage can be used for load leveling by charging during periods of high load and/or discharging during periods of low load.

A threshold load-leveling algorithm was implemented for the battery storage controller discussed in Section 2.2.5. In this regime, the controllers dispatch the energy storage systems to discharge equal to the positive difference between (or to charge equal to the negative difference between) net uncontrolled load (load minus generation) and a set threshold, subject to charging, discharging, and energy capacity limits. If the setpoint is sufficiently greater than the average load, this controller will tend to keep the batteries charged while shaving peaks that exceed the threshold. Conversely, if the setpoint is sufficiently lower than the average load, this controller will tend to keep the batteries discharged while shaving troughs below the threshold.

3.1.1 Setup

The threshold load-leveling algorithm was demonstrated using the testbed described in Section 2.0. As shown in Figure 6, the mean house load for the simulated day ranges between 1.14 kW and 2.78 kW. Two simulations were performed to demonstrate the load-leveling algorithm with different setpoints: 4.0 kW to demonstrate peak shaving and 0.0 kW to demonstrate PV export reduction.

3.1.2 Load Leveling for Peak Shaving – Results

Net meter load for the houses in the testbed are shown with and without peak shaving (threshold load leveling with setpoint 4.0 kW) in Figure 6.

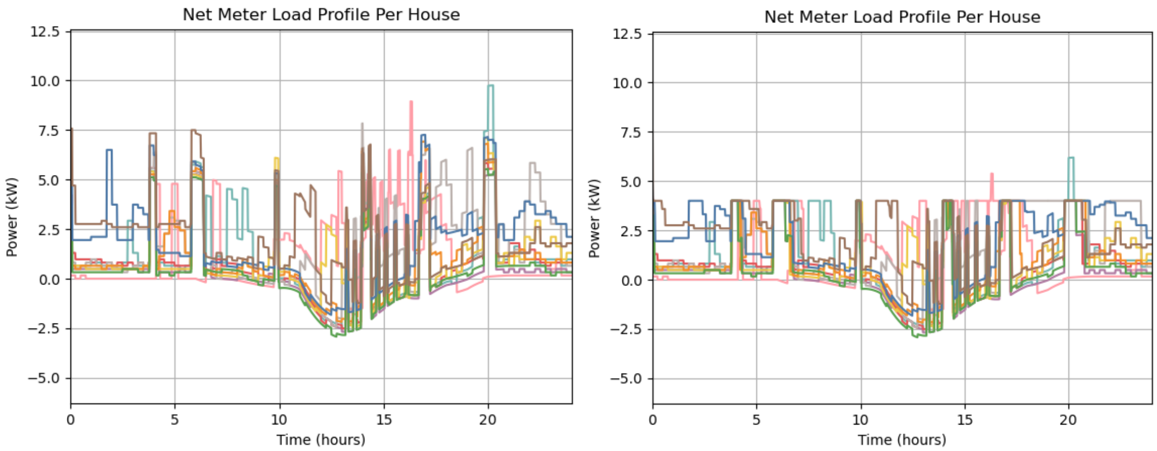

Figure 6. Net meter load – color coded by house – including residential load, solar PV generation, and any storage charging or discharging without energy storage (left) and with BTM storage controlled to shave load above 4.0 kW (right).

Introducing BTM storage with peak shaving control reduced the peak load for all houses. For eight out of ten houses, the controlled peak net load was reduced to the threshold setpoint of 4.0 kW. For the other two houses (houses 1 and 2), which had the highest overall uncontrolled peak net loads, the controlled peak net load exceeded the threshold only when the battery discharge was limited by physical constraints (i.e., the discharge limit of 1.8 kW per inverter). The power and energy usage of each energy storage unit are shown in Figure 7. Note that each unit (consisting of one inverter and one or more battery modules) is plotted individually, color coded by house.

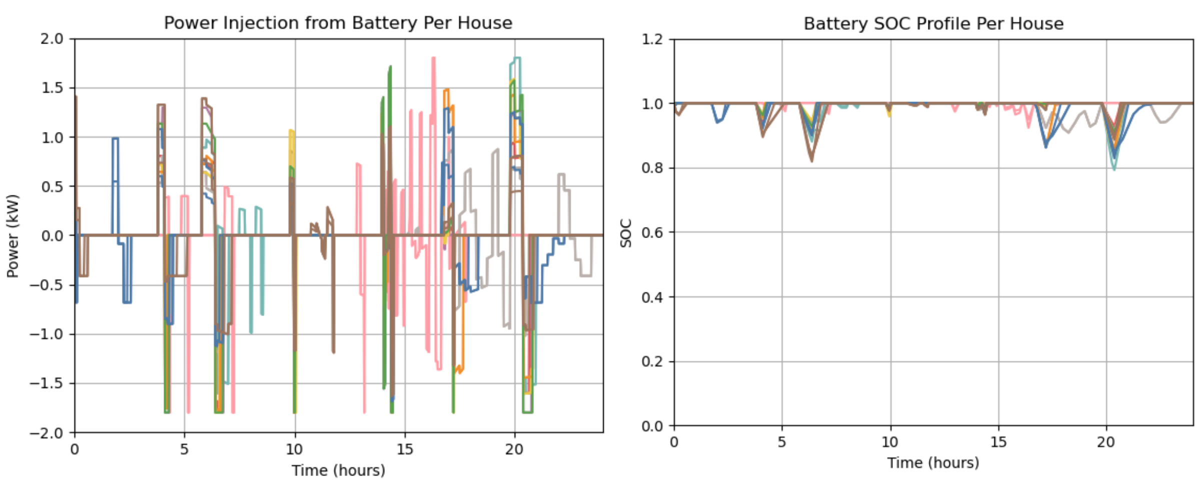

Figure 7. Energy storage units controlled to shave load above 4.0 W; power usage (left) and SOC (right); each color coded by house. Some houses have multiple energy storage units (see Section 2.2.5). Full peak shaving cannot be achieved when power discharge demand exceeds capacity.

Setpoint tracking for peak shaving was limited more by discharge (power) limits than by capacity (energy) limits. At approximately hour 16 (house 1) and hour 20 (house 2), the discharge limit was reached and the peak shaving setpoint could not be achieved. Only a fraction of the energy capacity (approximately 20%) of the systems was used in this application. The unused energy capacity could be leveraged by a multi-objective controller; alternatively, BTM storage systems intended for peak shaving applications could be built with less energy capacity.

Load-leveling control can reduce voltage variability. Load current causes a voltage drop across primary conductors, transformers, and secondary conductors. The higher current after low-voltage transformation corresponds to a greater voltage drop per unit length of conductor. While the testbed does not include a detailed model of customers outside of the ten house set (and therefore does not capture the full dynamic range of the distribution transformer voltage) the effects of peak shaving on the voltage drop across the transformer and secondary conductors are captured in Figure 8.

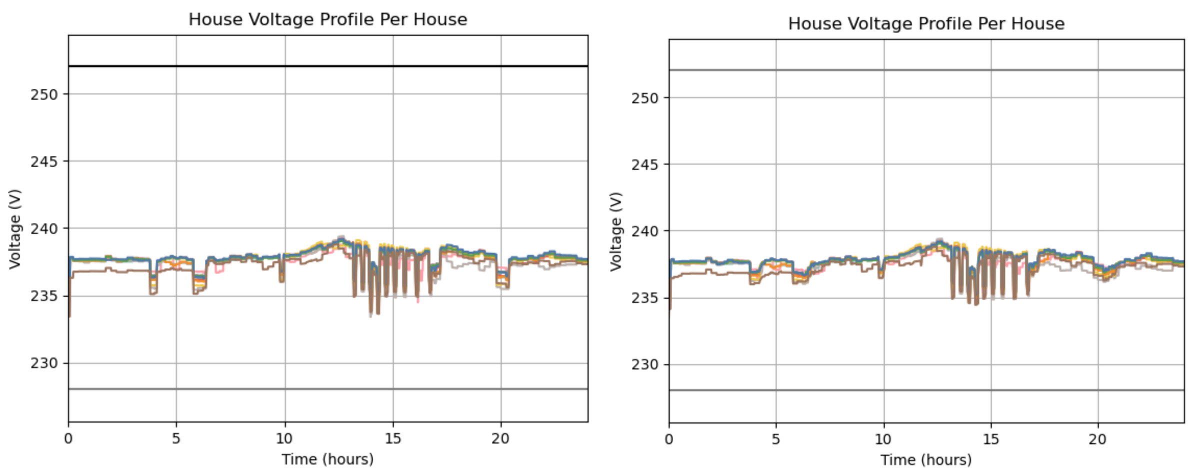

Figure 8 Residential split-phase line-to-line (240 V nominal) voltage at each meter – color coded by house – with ANSI C84.1 range A shown in black both without energy storage (left) and with BTM storage controlled to shave load above 4.0 kW (right).

Peak shaving reduced the depth of voltage troughs by reducing controlled net load during moments of peak power consumption. A voltage controller could improve these results further by monitoring voltage and controlling both magnitude and phase of the current waveform used to charge and discharge the energy storage systems (i.e., real and reactive power control.)

3.1.3 Load Leveling for PV Export Reduction – Results

Net meter load for the houses in the testbed are shown with and without PV export reduction (threshold load leveling with setpoint 0.0 kW) in Figure 9.

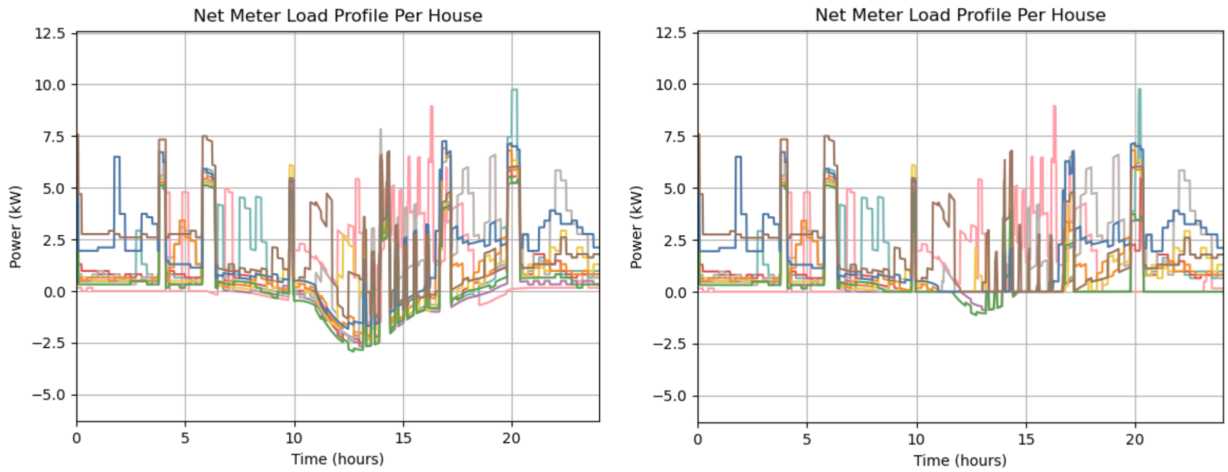

Figure 9. Net meter load – color coded by house – including residential load, solar PV generation, and any storage charging or discharging without energy storage (left) and with BTM storage controlled reduce solar PV export (right).

Introducing BTM storage with PV export reduction control reduced PV export for all houses. For eight out of ten houses, the controlled peak net load was held at or above the threshold setpoint of 0.0 kW (i.e., no PV export). The other two houses (houses 3 and 8), which each had only one inverter, PV export occurred when battery charging was limited by physical constraints (i.e., the charge limit of 1.8 kW). The power and energy usage of each energy storage unit are shown in Figure 10. Note that each unit (consisting of one inverter and one or more battery modules) is plotted individually, color coded by house.

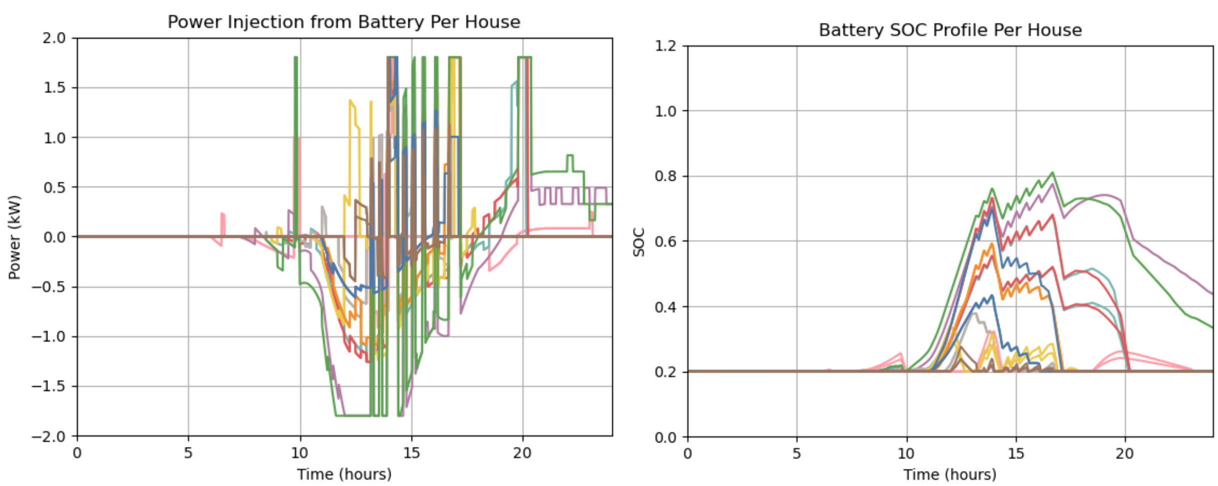

Figure 10. Energy storage units controlled to reduce PV export; power usage (left) and SOC (right); each color coded by house. Some houses have multiple energy storage units (see Section 2.2.5). Full PV export reduction cannot be achieved when power charge demand exceeds capacity.

Setpoint tracking was limited more by charge (power) limits than by capacity (energy) limits. Between approximately hours 12 and 15, the charging limit was reached for houses 3 and 8 and the PV export setpoint could not be achieved. For houses 3 and 8, the SOC does not return to the 20% baseline by the end of the 24-hour period and the systems would continue discharging at the beginning of the following day. For most houses, more of the available energy capacity (SOC headroom) was used (approximately 75%); however, SOC headroom is still available for multi-objective control.

3.2 Scenario 2: Load Shifting

The second scenario explored in this analysis implements load shifting in response to TOU pricing. This section describes the TOU pricing structure used in the scenario and discusses the impacts of load shifting on power consumption BTM.

The TOU price structure implemented in this load-shifting scenario is based on the Demand Response-Solar Energy System (DR-SES) TOU schedule, common for residential customers of San Diego Gas & Electric.[8] The DR-SES TOU schedule, shown in Figure 11, has three tiers. The lowest price tier is called “Super Off-Peak,” the mid-price tier, “Off-Peak,” and the most expensive price tier, “Peak.”

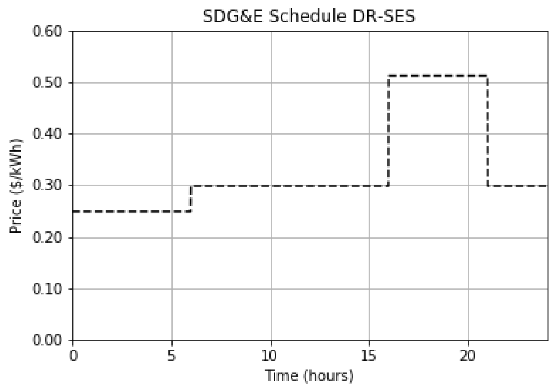

Figure 11. TOU Schedule for residential customers in San Diego Gas & Electric territory with rooftop solar.

The date of this scenario falls on a weekday in the summer TOU period. On weekends, the Super Off-Peak period extends until 2:00 p.m. The price in each period in winter months is less than the summer months. Prices shown correspond to the total rate billed to the customer per kWh, comprising UDC (utility distribution), DWR (division of water resources bond charge), and EECC (electric energy commodity cost). Although customers on this tariff are billed a minimum cost per day of $0.338, this was not reflected in the analysis.

The customer households in this scenario are given a billing period of one day to mirror the analysis window. The total usage in each price tier for the billing period is multiplied by the price of electricity for that tier. Customers with PV installed are placed on an additional tariff to allow them to participate in Net Energy Metering (NEM).[9] This analysis presents the costs associated with net consumption for one day and an example of credits accumulated by the customer for net generation in each of the three price tiers.

[8] http://regarchive.sdge.com/tm2/pdf/ELEC_ELEC-SCHEDS_DR-SES.pdf

[9] http://regarchive.sdge.com/tm2/pdf/ELEC_ELEC-SCHEDS_NEM-ST.pdf

3.2.1 Setup

The goal of the load-shifting algorithm is to reduce the cost to the customer over one day. The customer has knowledge of the cost of electricity in each hour of the day. To enable load shifting, the BTM storage system is instructed to charge (if it is physically capable of doing so) prior to the Peak period, and discharge once the On-Peak period begins. As the Peak period is followed by an Off-Peak period (not as inexpensive as Super Off-Peak), the battery is instructed to continue to discharge as available.

3.2.2 Load Shifting – Results

Figure 12 shows the simulated SOC throughout the day for each energy storage unit.

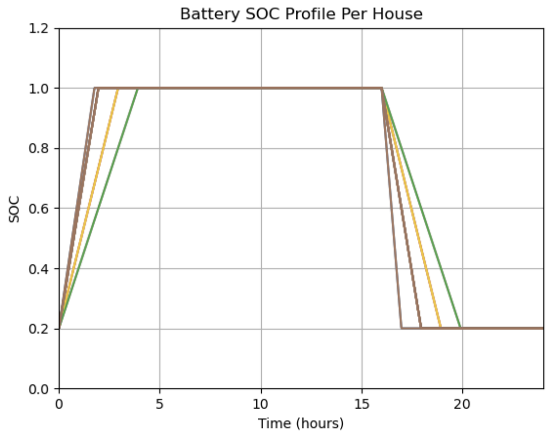

Figure 12. Energy storage unit SOC profile with load shifting.

Following the load shifting instructions, all units charge at their charge limit until the Peak period begins at 4:00 p.m. At that time, all batteries discharge at their discharge limit until they reach their minimum SOC (20%). The fill rate of the energy storage unit's SOC is a function of the number of inverters and battery modules installed, where fewer inverters and/or more battery modules correspond to a shallower rate of filling/emptying.

Figure 13 shows the power injected at each house from each energy storage unit.

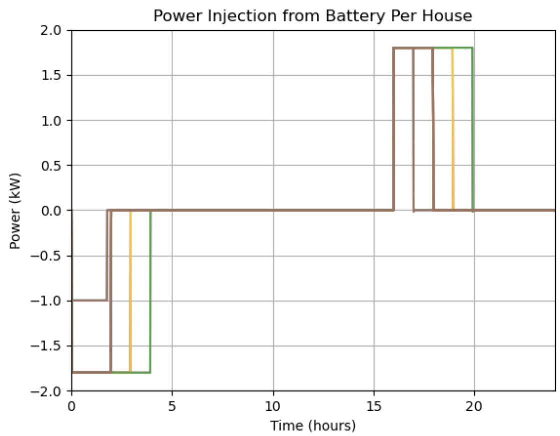

Figure 13. Power injected into each house from battery providing load shifting.

As with the SOC, units with fewer inverters and/or more battery modules will have the ability to charge and discharge for a longer duration.

The net load profiles for each house without energy storage are shown in Figure 14 (left), mirroring the profiles in Figure 8 (left). When BTM storage is added to the houses with the goal of shifting the load to low-price periods, net load increases in the Super Off-Peak period and decreases in the Peak period (Figure 14, right). The energy storage units always charged until they reached 100% SOC at the beginning of the day and discharge until 20% SOC when the Peak period starts. This is demonstrated by the difference in the net load profiles in Figure 14.

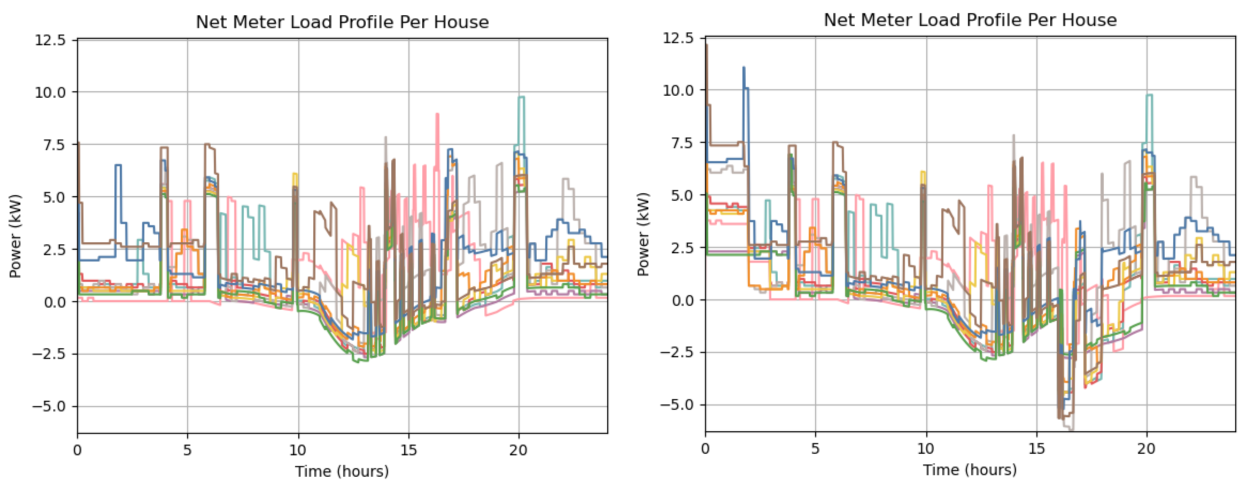

Figure 14. Load profiles at each house without load shifting (left) and with (right).

Net load increases until the energy storage units saturate their charge (roughly before 5:00 a.m.) and decreases once the Peak period starts.

The net energy consumptions without and with load shifting are shown in Figure 15.

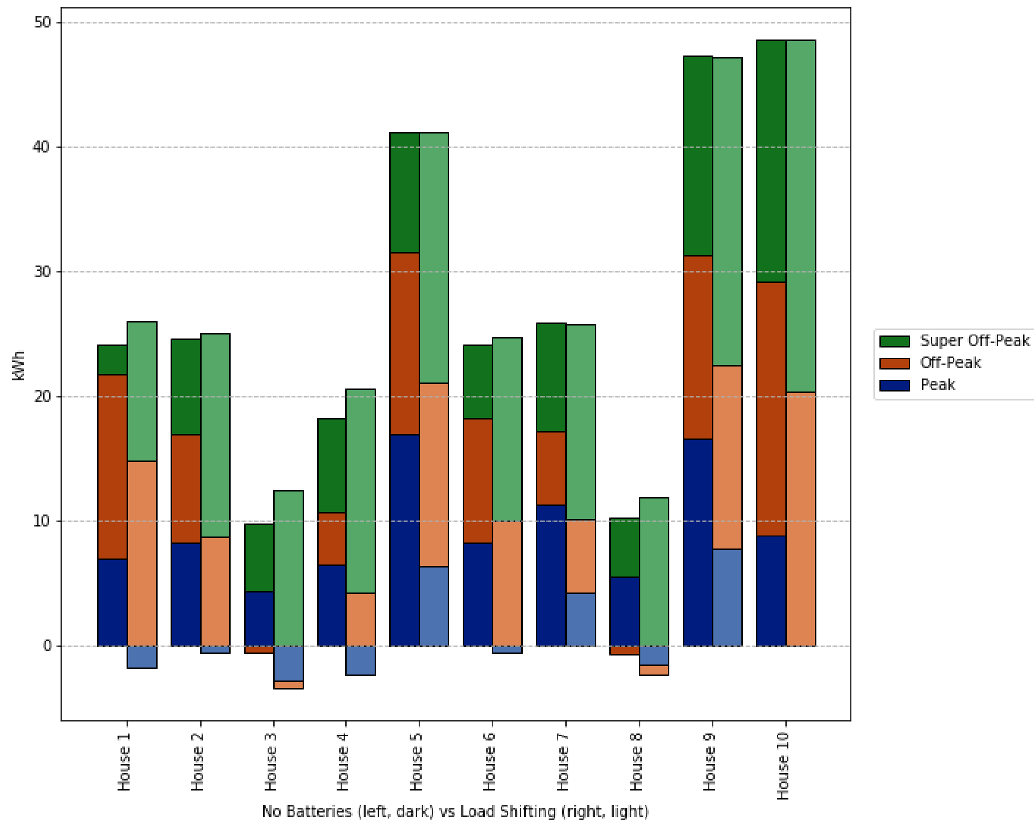

Figure 15. Shift of load from high-price to low-price tiers.

Green indicates the Super Off-Peak tier, orange the Off-Peak tier, and blue the Peak tier. The introduction of load shifting using BTM storage increased the total consumption in the Super Off-Peak tier for all the houses. Where possible, consumption in the Off-Peak and Peak tiers was also shifted to generation in these tiers (houses 1, 2, 3, 4, 6, and 8) in response to the signal to discharge energy in the Peak tier.

The value of the electricity consumed and exported is shown in Figure 16 and Figure 17. The net consumption and generation are calculated according to the TOU tariff. For example, house 3 was a net exporter of energy on this summer day in the Off-Peak tier prior to including energy storage. With load shifting, house 3 became a net exporter in the Off-Peak and Peak tiers. Although NEM credits for net export in the summer are often offset by net consumption in the winter, the daily revenue is shown in Figure 16 for illustration purposes.

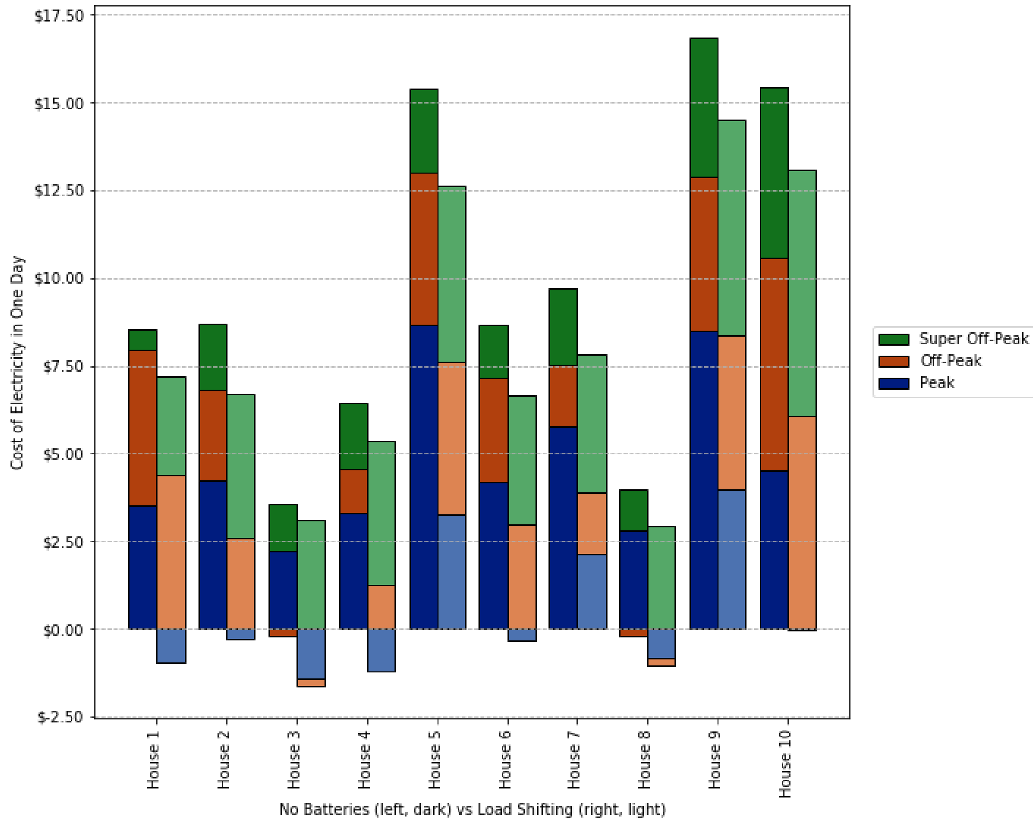

Figure 16. Cost of electricity in one day -- NEM credits included.

Figure 17 demonstrates that – even without NEM credits – load shifting due to small scale batteries will reduce a household's daily cost of electricity.

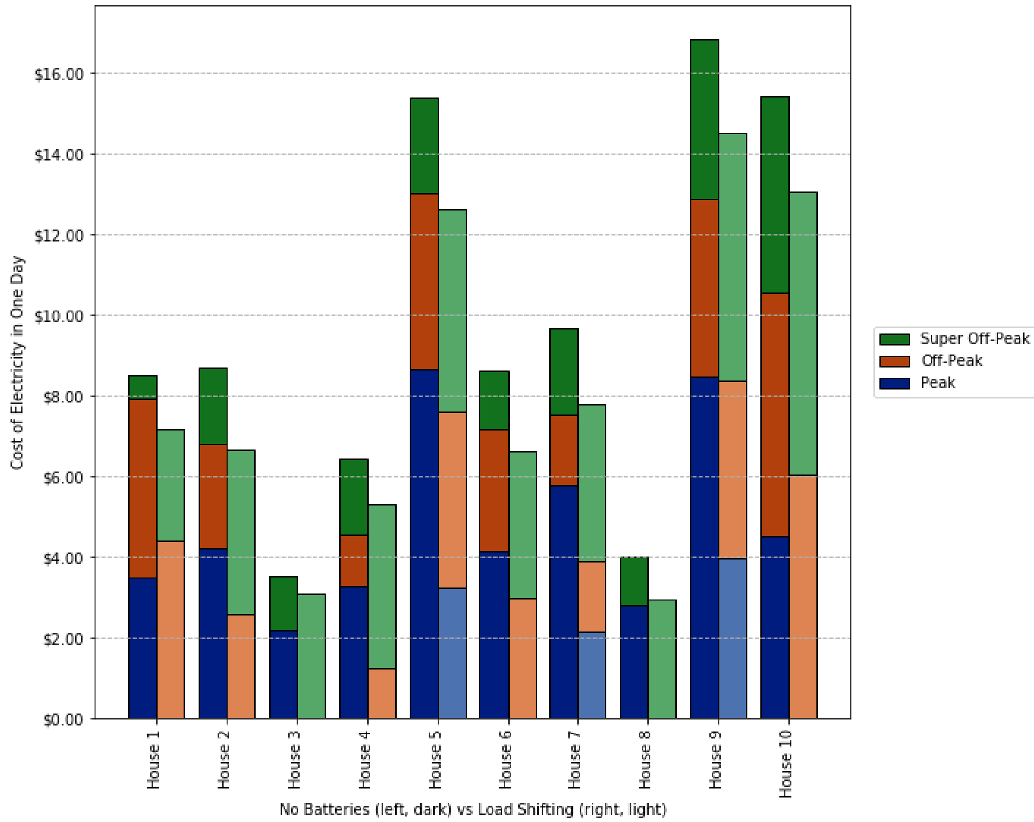

Figure 17. Cost of electricity in one day -- no daily NEM credits.

The bulk of the consumption has shifted to Super Off-Peak and Off-Peak tiers. While the total consumption is equal or slightly higher (Figure 14), the cost incurred for this usage is much less than the Peak tier. Load shifting enables percent daily cost savings between 13% and 26% (Table 6).

Table 6. Percent cost savings on daily energy consumption due to load shifting.

	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8	House 9	House 10
Percent Savings	16%	23%	13%	17%	18%	23%	19%	26%	14%	15%

4.0 Discussion

In this work, PNNL developed a co-simulation testbed composed of interaction between the grid, high-fidelity end-use loads, BTM PV systems and BTM storage systems with controllers. The testbed was used to demonstrate the capability of BTM storage systems for residential customers with two control routines: load leveling and load shifting.

It is shown here that a simple setpoint-tracking load-leveling control can be used to reduce load variability either by achieving peak load shaving or by reducing PV export. In both cases, the storage capacity was not fully utilized as the performance was limited by the storage charging-discharging limits. For example, the peak shaving algorithm only used 20% of the energy capacity. This result suggests that a future multi-objective controller could leverage the storage capacity more efficiently.

Further, PNNL implemented a TOU-based load-shifting control and analyzed its impact on the customer's electricity cost. The simulation results show the load shifting control enables between 13% and 26% daily cost savings for the customers while utilizing the full capacity of the storage system during the peak price hours. It is worth noting that peak price hours and peak PV generation hours do not typically overlap. This suggests that a load shifting control with prior knowledge of TOU pricing combined with PV export reduction control could maximize the direct economic benefits to the customers.

The results presented in this report show that BTM storage systems have the potential to positively affect customer side as well as grid side performance. Furthermore, the findings may assist BTM storage system vendors to define revenue-maximizing control algorithms and appropriately size inverter and storage capacity.

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