Can Solar PV Boost the Value of Behind-the-Meter Battery Storage?

An Analysis of Residential and Non-Residential Systems in SDG&E's Service Territory

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Table of Contents

1 Summary

Battery energy storage systems (BESS) are increasingly being installed in both residential and commercial applications, and often the batteries are paired with solar photovoltaic (PV) systems. However, many system owners and even installers struggle to accurately estimate the potential benefits of solar-paired battery systems relative to stand-alone battery systems. Variability in building loads and solar energy production, nuances of battery system operating characteristics, and complex electric rate structures require sophisticated tools to analyze the economic implications of pairing batteries and solar PV. To shed light on potential synergies between BESS and PV, Lumidyne performed detailed analyses of bill savings for several system configurations and customer types.

We quantified the bill savings for behind-the-meter (BTM) battery energy storage systems in San Diego Gas & Electric's (SDGE) service territory and found economic synergies for solar-paired battery systems hosted by non-residential customers, but residential systems did not exhibit the same synergies. Anecdotal evidence in the industry has suggested there can be beneficial interactions between BTM solar PV and batteries; however, it is not typically quantified. Our analysis shows that significant synergies are possible but case specific. This report discusses circumstances that can lead to PV and BESS economic synergies and the circumstances that can harm BESS economics when paired with solar. We also call attention to how SDGE customers are adopting BESS in a manner inconsistent with the greatest economic benefits.

Lumidyne collaborated with E Source in early 2020 to develop bill savings, system economics and customer adoption forecasts of BTM battery storage for SDGE customers. SDGE has some of the highest rates of BESS and PV adoption among US utilities, providing an interesting case study. The published results and methodology of our analysis are included in the Behind-the-Meter Battery Market Study; the insights presented in this article are adapted from that effort.

Key insights revealed in this study include:

Non-Residential Key Insights

- Incremental bill savings from installing BESS can be greater when paired with solar
- Solar-paired BESS can lead to greater demand reductions because PV makes it easier for BESS to reduce on-peak demand using less stored energy
- Despite solar-paired BESS's better economics, historical non-residential adoption has favored stand-alone BESS

Residential Key Insights

- Incremental bill savings from installing BESS can be greater for a stand-alone BESS than for a system paired with PV.
- Lack of residential demand charges makes energy arbitrage the sole economic opportunity
- The investment tax credit's requirement that solar-paired BESS charge entirely with PV energy, rather than with low-cost nighttime energy, limits the system's ability to profit from energy arbitrage
- Minimum bill charges erode solar-paired BESS's bill savings
- Despite being generally non-cost-effective, residential BESS represents a sizable percentage of total historically-installed BTM battery capacity

To demonstrate the economic synergy, or lack thereof, between PV and BESS, the remainder of this report describes:

- Modeled system sizes and characteristics
- SDGE electric rates considered
- Optimal battery charging and discharging strategies
- Pre- and post-BESS utility bills and bill savings for stand-alone versus solar-paired systems
- Key factors leading to the presence or absence of synergy between PV and BESS
- Possible explanations for customer adoption behavior

To begin we focus on non-residential systems, where economic synergies were found, and move to residential systems, where BESS economics suffered when paired with solar. We conclude with a discussion of historical customer adoption behavior.

2 Non-Residential BESS

The following sections describe our modeling assumptions, results and takeaways for non-residential BESS.

System Sizes and Characteristics

We modeled prototypical customers using average customer characteristics observed in SDGE's territory. SDGE provided aggregate hourly load shapes for residential and non-residential customers, which we scaled to represent load shapes for an average home and commercial premise. SDGE also provided measured solar irradiance profiles that formed the basis for our hourly solar generation shapes. We chose system sizes and characteristics near the average characteristics found in the SDGE Advanced Energy Storage Systems and the California Distributed Generation Statistics databases for BESS and PV, respectively.

Non-Residential Building and System Characteristics

Building	
Annual Consumption (kWh/year)	478,346
Peak Load (kW)	84

Solar PV	
PV System Size (kW-DC)	110
PV Capacity Factor (%)	19%
Annual Consump. Met by Solar (%)	38%

Battery	
Energy Rating (kWh)	100
Power Rating (kW)	50
Storage Duration (hours)	2
Roundtrip Efficiency (%)	90%

Electric Rates

We focused on SDGE's AL-TOU Secondary rate because it is common among non-residential customers. In addition to time-of-use (TOU) energy charges, this rate includes additive on-peak and non-coincident demand charges. The maximum monthly demand occurring between 4pm and 9pm is charged at on-peak demand rates, while the maximum monthly demand across all hours of the day (and bounded to not fall below 50% of the *annual* maximum demand) is charged at non-coincident demand rates.

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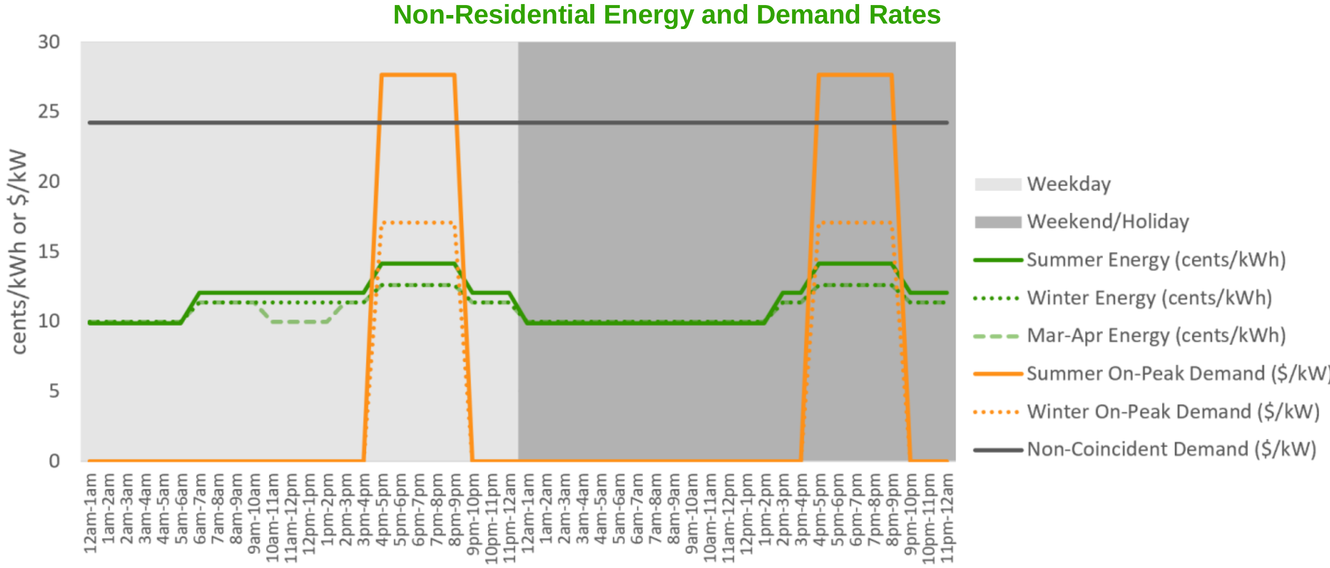
Energy charges are differentiated by three time-of-use periods: super off-peak, off-peak and on-peak. During the summer months of June through October, the ratio of on-peak to super off-peak energy charges is 1.43:1, and the on-peak to off-peak ratio is 1.26:1. During winter months, the ratio of on-peak to super off-peak energy charges is 1.17:1, and the on-peak to off-peak ratio is 1.11:1. During March and April when systemwide load is low and PV output is high, the super off-peak period extends to include 10am to 2pm on weekdays. On this rate schedule a BESS having a 10% roundtrip efficiency loss can profit from energy arbitrage in all seasons and multiple TOU periods.

Non-Residential Energy and Demand Rates



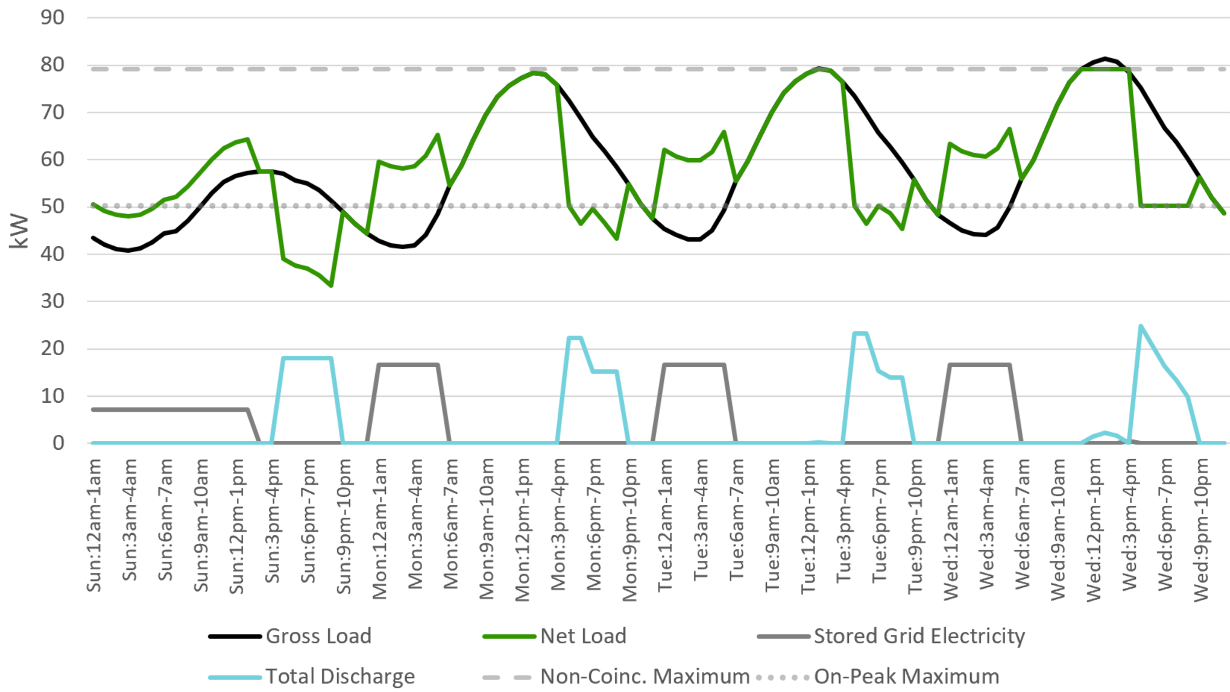
Optimal Dispatch Strategy – Stand-Alone BESS

We employed Lumidyne's Spatial Penetration and Integration of Distributed Energy Resources (SPIDER™) model to calculate a theoretically optimal charging and discharging strategy for stand-alone and solar-paired battery systems using the hourly building and solar load shapes, the selected electric rates and the chosen system characteristics. SPIDER's BESS dispatch optimization algorithm, formulated as a mixed-integer linear program, provides a theoretical optimum because it assumes perfect foresight of building and solar loads.

For non-residential stand-alone battery systems, optimal battery dispatch reduces on-peak demand charges occurring between 4-9pm. Additionally, optimal dispatch reduces non-coincident peaks on days with greatest loads. On days with lower loads and stored energy exceeding that required to minimize on-peak demand charges, the BESS also reduces on-peak energy charges. All charging of the stand-alone battery occurs during super off-peak hours occurring late at night and early morning when energy prices are lowest.

The difference between “gross” building loads prior to the BESS (shown in black) and “net” building loads after the BESS (shown in green) are apparent in the figure below, which depicts several days in October for a prototypical premise in the coastal climate region.

Dispatch of Non-Residential Stand-Alone BESS



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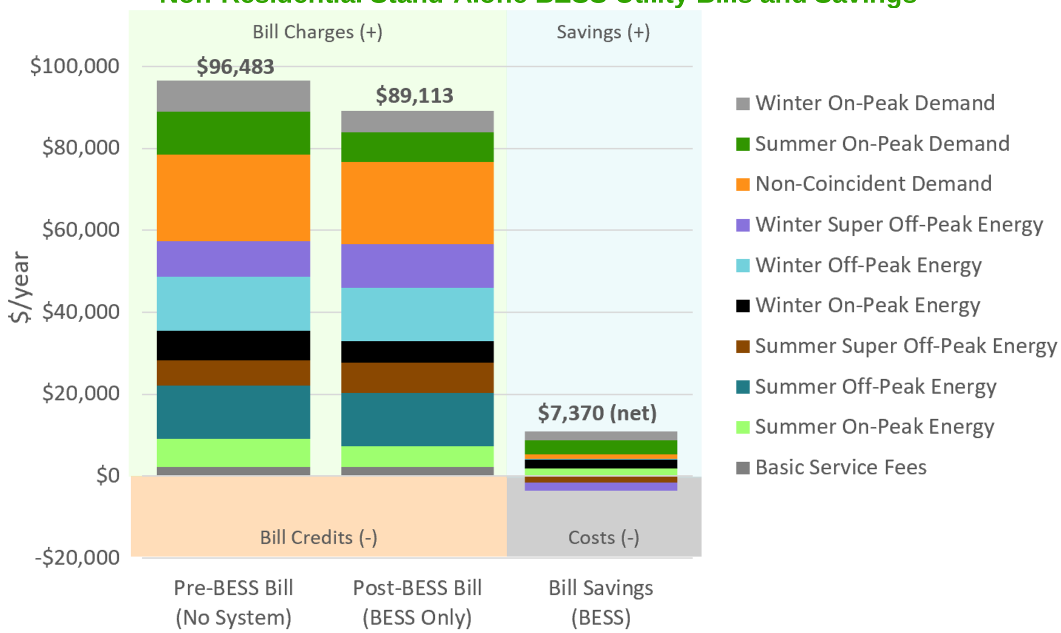
Pre- and Post-BESS Utility Bills and Savings – Stand-Alone BESS

The SPIDER model used the hourly pre-BESS and post-BESS building load shapes to evaluate annual utility bills broken out by rate component. The difference between pre-BESS and post-BESS annual utility bills is the annual bill savings resulting from the battery system. The modeled non-residential stand-alone battery system achieves a $7,370 per year, or 7.6%, net reduction in utility bills relative to a building with no systems.

Non-Residential Stand-Alone BESS Utility Bills and Savings

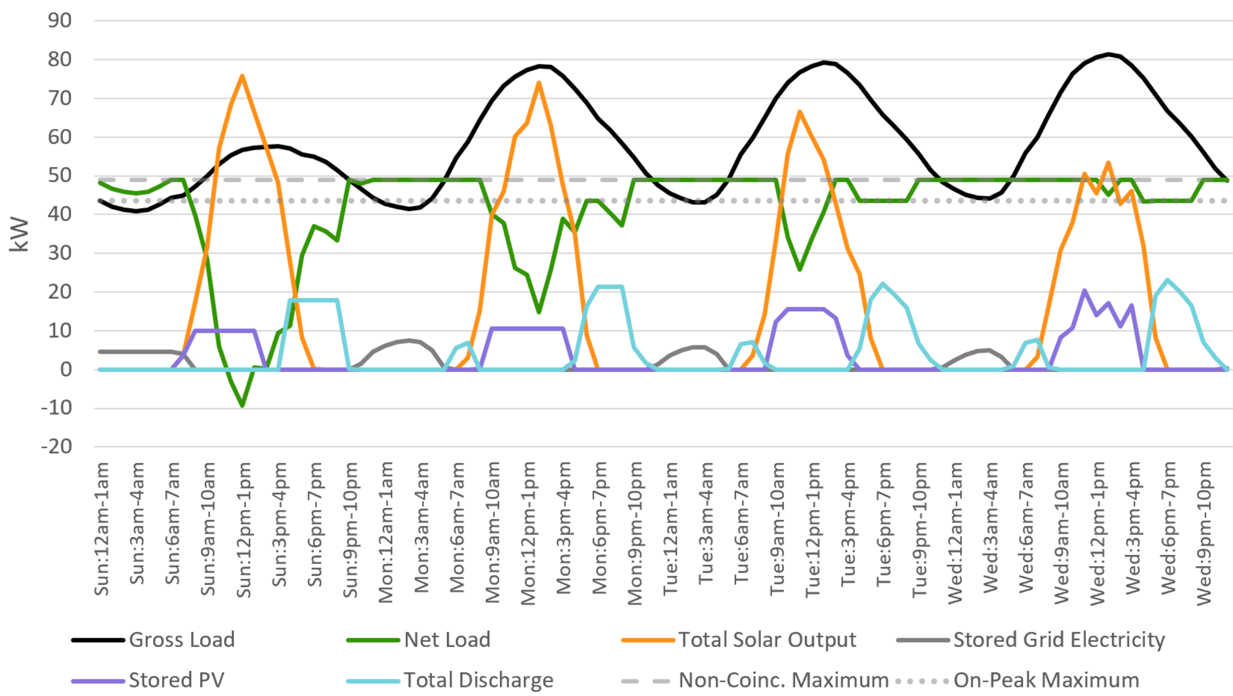


Optimal Dispatch Strategy – Solar-Paired BESS

We also evaluated the optimal dispatch of a BESS added to a PV-equipped building to compare against the performance and economics of a stand-alone battery system. The non-residential solar-paired BESS still prioritizes reducing on-peak demand charges, but it has greater ability to reduce non-coincident demand charges relative to stand-alone BESS.

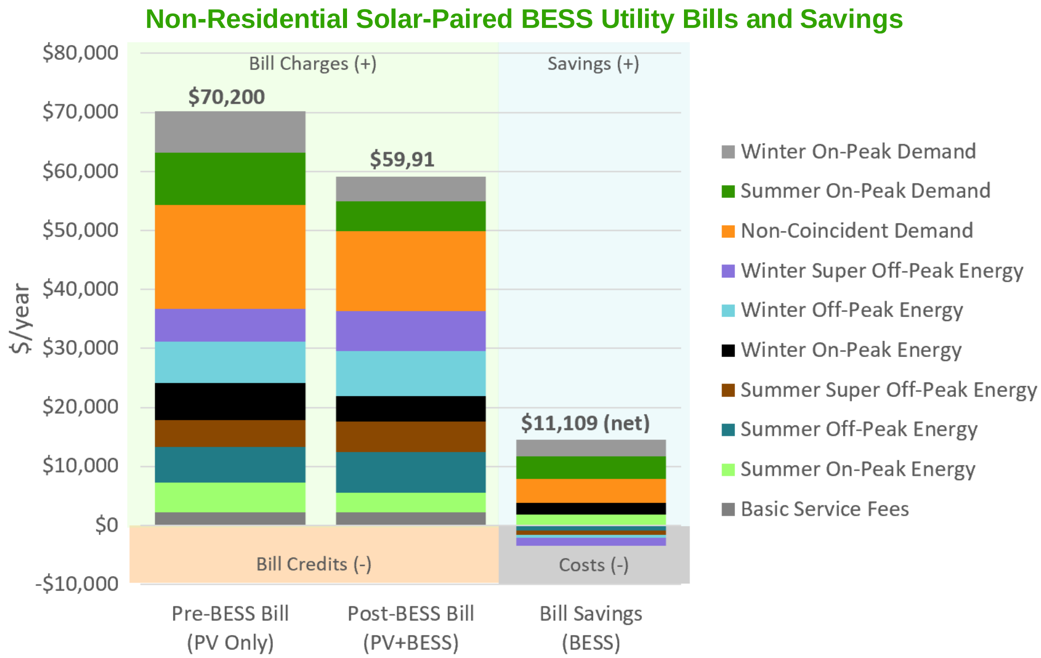
Owing to PV's ability to offset a significant portion of midday non-coincident demand, solar-paired BESS is able to reduce dual demand peaks occurring during the morning and evening when sunlight is minimal. This synergy between the PV and BESS systems leads to greater on-peak and non-coincident demand reductions than stand-alone BESS. Additionally, as illustrated in the figure below for several days in October, solar-paired BESS stores most of its energy from midday solar generation compared with nighttime grid electricity. Though less optimal for bill savings, charging primarily from midday solar energy is a requirement to receive the [commercial federal investment tax credit] (ITC), which reduces initial BESS installation costs and outweighs the foregone bill savings.

Dispatch of Non-Residential Solar-Paired BESS



Pre- and Post-BESS Utility Bills and Savings – Solar-Paired BESS

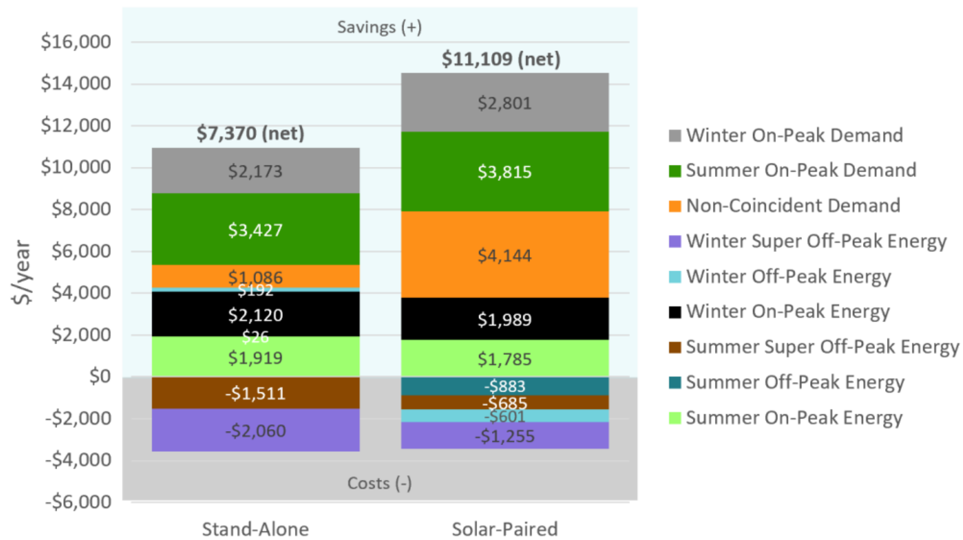
We estimated annual utility bills by rate component for solar-paired BESS in a manner similar to that used for stand-alone BESS. The modeled non-residential solar-paired battery system achieves a $11,109, or 15.8%, reduction in annual utility bills relative to a building with solar PV.



Bill Savings Comparison

Comparing annual bill savings for non-residential stand-alone and solar-paired battery systems shows the synergy between the PV and BESS systems leads to a 50% increase in bill savings relative to stand-alone BESS. The boost in solar-paired bill savings is attributable to an additional $4,074 per year reduction in demand charges. However, solar-paired BESS also leads to a $335 net increase in energy charges relative to stand-alone BESS due to the need to charge using midday solar energy rather than lower-cost nighttime energy. Energy arbitrage plays a small role in bill savings, whereby stand-alone BESS achieves 91% of its bill savings from demand reductions (compared with energy arbitrage), and solar-paired BESS achieves 97%.

Bill Savings Comparison for Non-Residential Stand-Alone versus Solar-Paired BESS

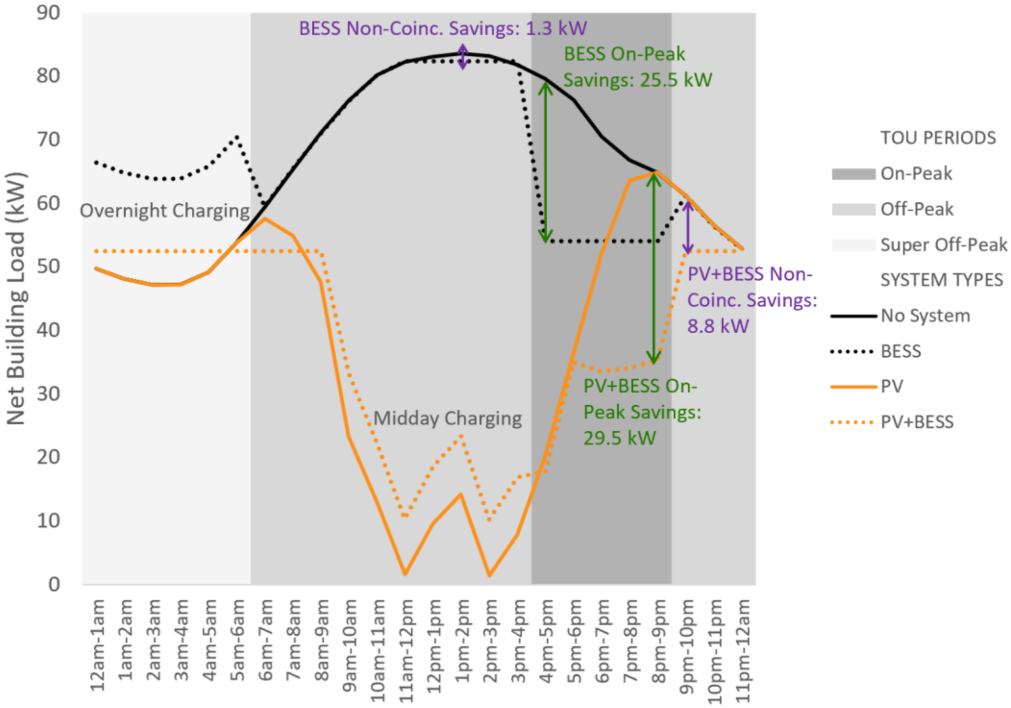


Factors Leading to Solar-Paired Synergy

Close inspection of a single weekday in July highlights how synergy between non-residential PV and BESS amplifies achievable demand savings. The PV system creates two peaks that BESS can shave, whereas a building without PV has a single, but wider, peak. Importantly, the PV system creates a narrower peak during the 4-9pm on-peak hours, meaning the BESS requires less energy to reduce demand during that period.

For example, during the illustrative day, solar-paired BESS requires 75.4 kWh of discharged energy to reduce demand by 29.5 kW during the on-peak period, giving a ratio of 2.56 kWh per kW of on-peak demand reduction. By comparison, stand-alone BESS requires 87.5 kWh of discharged energy to reduce on-peak demand by 25.5 kW, a ratio of 3.43 kWh per kW.

Pre- and Post-BESS Net Building Load for Stand-Alone versus Solar-Paired BESS for a July Weekday



Since solar-paired BESS requires less energy to reduce an equivalent amount of on-peak demand, more stored energy remains to reduce on-peak or non-coincident demand or to provide additional energy arbitrage opportunities. Across the entire year, solar-paired BESS uses that additional stored energy to increase on-peak demand savings by 18% and non-coincident demand savings by 380%. In doing so, solar-paired BESS discharges only 2% more energy throughout the year than stand-alone BESS.

3 Residential BESS

The subsequent sections describe our modeling assumptions, results and takeaways for residential BESS.

System Sizes and Characteristics

We based residential prototypical customers on average customer characteristics observed in SDGE's territory. Again, we chose system sizes and characteristics near the average characteristics found in the SDGE Advanced Energy Storage Systems and the California Distributed Generation Statistics databases for BESS and PV, respectively.

Residential Building and System Characteristics

Building	
Annual Consumption (kWh/year)	11,275
Peak Load (kW)	2.3

Solar PV	
PV System Size (kW-DC)	6
PV Capacity Factor (%)	19%
Annual Consump. Met by Solar (%)	90%

Battery	
Energy Rating (kWh)	13.2
Power Rating (kW)	5
Storage Duration (hours)	2.6
Roundtrip Efficiency (%)	90%

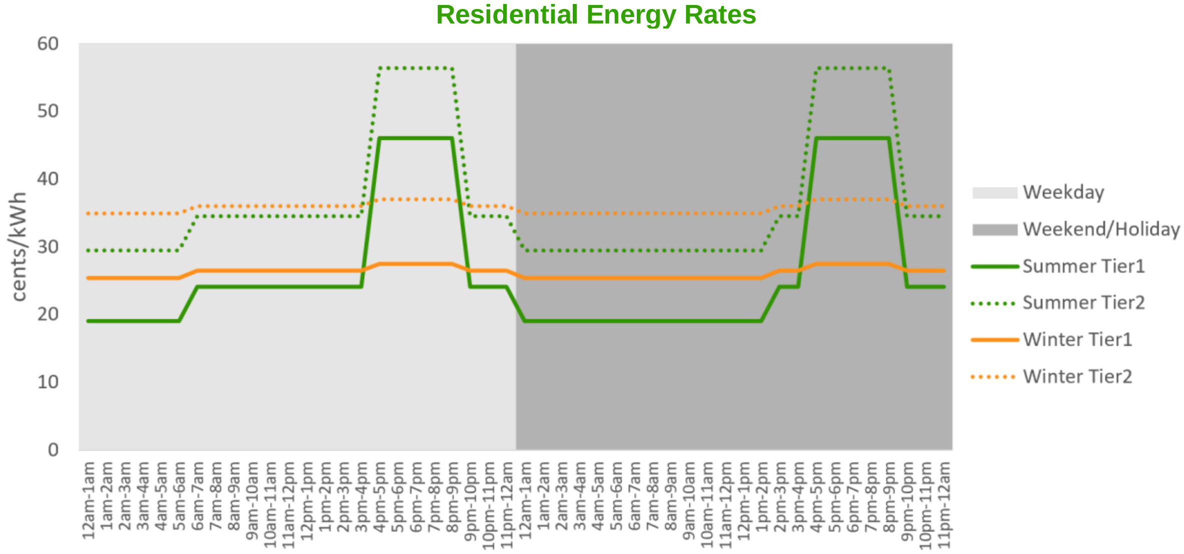
Electric Rates

The residential analysis relied on SDGE's TOU-DR1 tariff because, though recently implemented, it was expected to gain high subscription among residential customers. This rate has no demand charges, but it does have two-tiered energy charges. For the coastal climate region depicted in these results, Tier 1 charges are applied to monthly consumption up to 351 kWh per month during summer months and 359 kWh during winter months. Consumption above those thresholds is charged at higher Tier 2 rates.

Energy charges are differentiated by three time-of-use periods: super off-peak, off-peak and on-peak. During the summer months of June through October, the ratio of on-peak to super off-peak energy charges is 2.41:1 for Tier 1 and 1.92:1 for Tier 2. The ratio of on-peak to off-peak energy charges is 1.91:1 for Tier 1 and 1.64:1 for Tier 2. For winter months, the energy charge ratios between TOU periods never exceed 1.08:1, meaning that a BESS with a 10% roundtrip efficiency loss has no incentive to operate because it cannot profit from energy arbitrage.

Lastly, the residential rates include a minimum bill charge of $0.338 per day, or about $10.28 per month.

Residential Energy Rates



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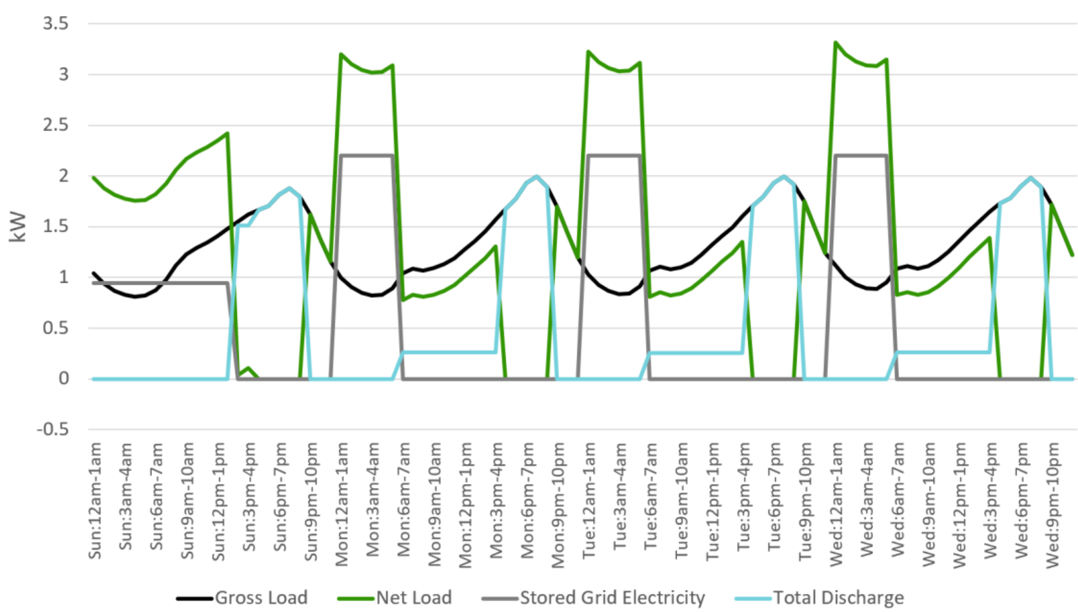
Optimal Dispatch Strategy – Stand-Alone BESS

The optimal dispatch for residential stand-alone BESS primarily offsets 4-9 p.m. on-peak energy consumption. Stand-alone BESS uses any excess stored energy to reduce off-peak consumption. All charging of stand-alone BESS occurs during the nighttime super off-peak hours. The battery does not operate during winter months because the price spread between TOU periods does not enable profitable energy arbitrage. The difference between "gross" building loads prior to the BESS (shown in black) and "net" building loads after the BESS (shown in green) is apparent in the figure below, which illustrates several days in the month of October for a prototypical home.

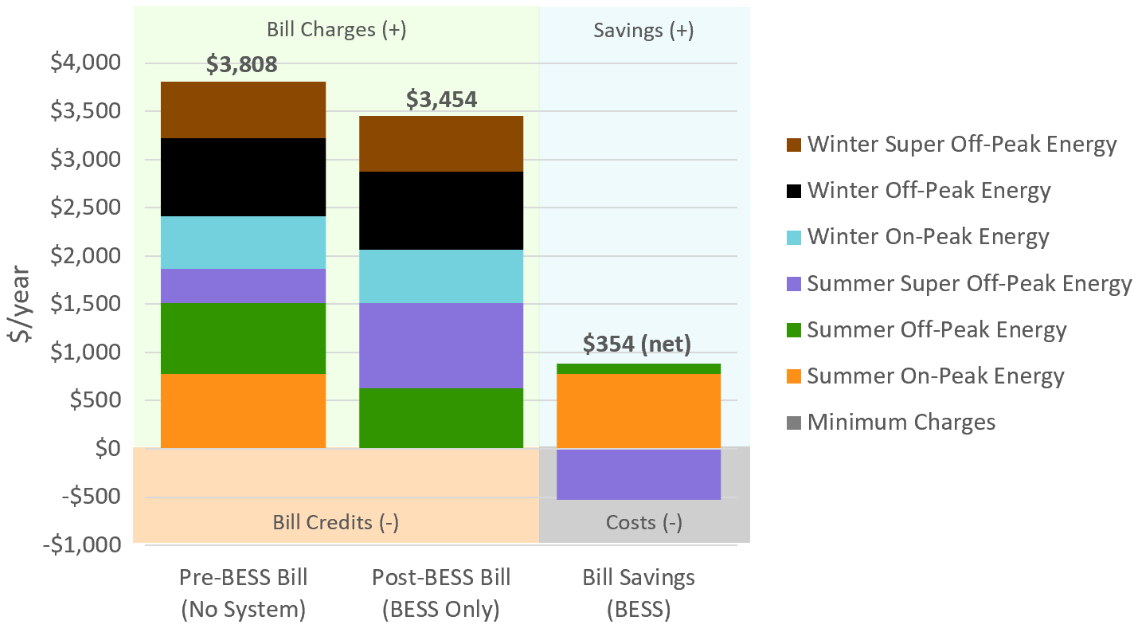
Dispatch of Residential Stand-Alone BESS



Pre- and Post-BESS Utility Bills and Savings – Stand-Alone BESS

Residential stand-alone BESS generates a reduction of $354 per year, or 9%, in annual utility bills. The modest bill savings are partly due to the battery only operating for five summer months (June through October) and remaining inactive during the remaining winter months. The figure below highlights that the BESS eliminates all summer on-peak energy charges and that battery charging occurs exclusively during the super off-peak period.

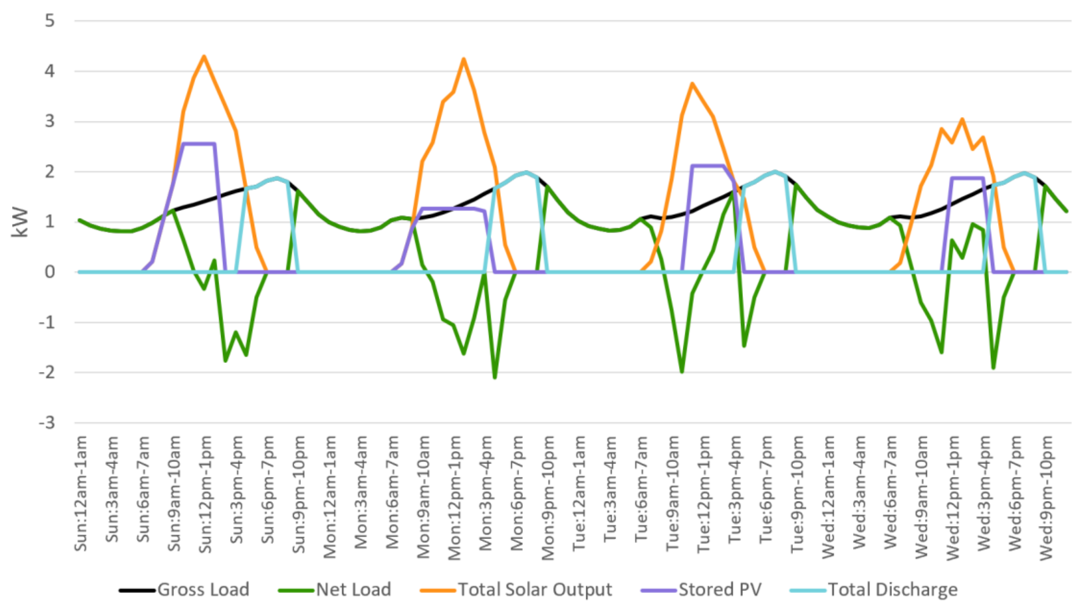
Residential Stand-Alone BESS Annual Utility Bills and Savings



Optimal Dispatch Strategy – Solar-Paired BESS

The optimal dispatch of solar-paired BESS relies on midday charging from solar to completely offset on-peak consumption at the expense of increasing off-peak consumption. Solar-paired BESS must exclusively use solar energy for charging to receive the residential federal investment tax credit. Since PV is typically generating during off-peak periods (with weekends/holidays being exceptions), it is not economical to use that solar energy to charge the battery and then discharge (after incurring roundtrip efficiency losses) back into the off-peak period. However, the monetary benefit of the federal ITC outweighs the foregone bill savings resulting from midday charging. The figure below depicts several days of optimal dispatch during October.

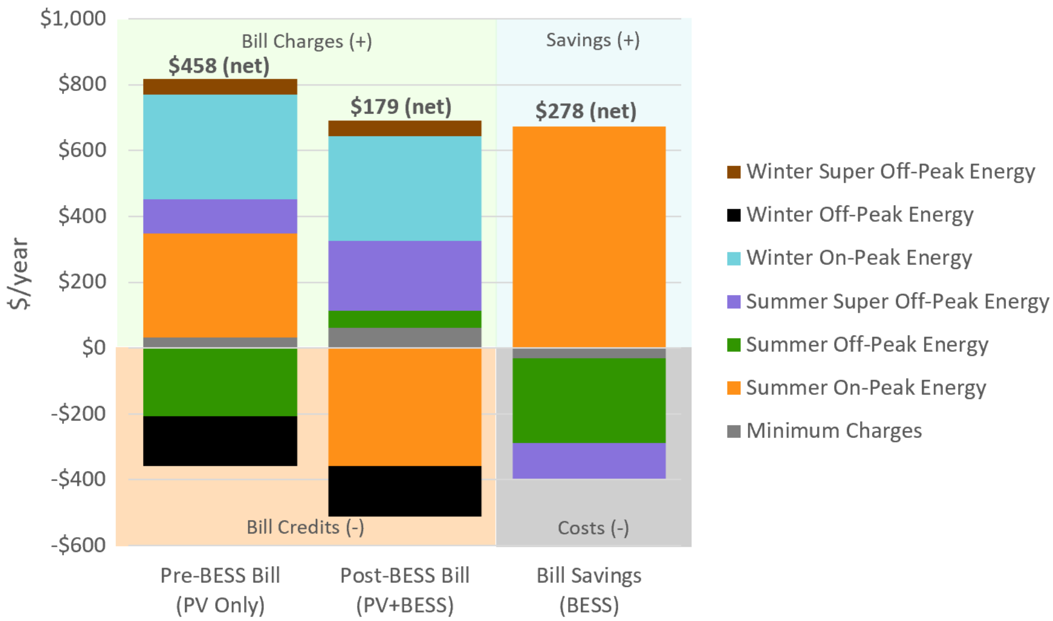
Dispatch of Residential Solar-Paired BESS



Pre- and Post-BESS Utility Bills and Savings – Solar-Paired BESS

Residential solar-paired BESS achieves a $278 per year, or 61%, net reduction in annual utility bills relative to a residence having only a PV system. All bill savings are generated by reductions in summer on-peak consumption, but 59% of those savings are cancelled out by increases in summer off-peak and super off-peak consumption and minimum bill charges. Though the modeled electric rates allow full net metering, minimum bill charges are imposed when a given month's utility bill falls below $10.28. In effect, minimum bill charges erode 10% of the incremental savings from the BESS.

Residential Solar-Paired BESS Annual Utility Bills and Savings

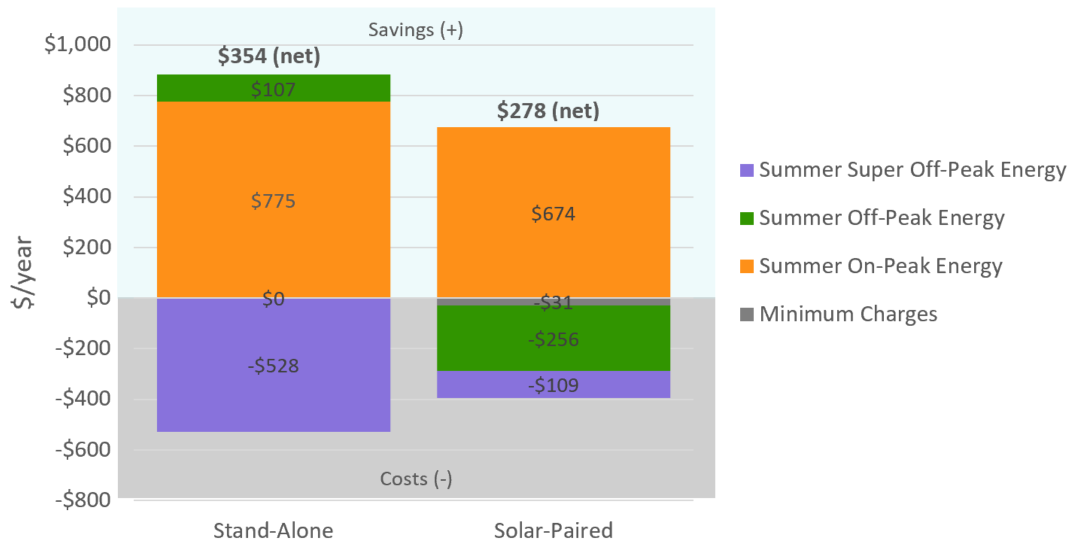


Bill Savings Comparison

Annual bill savings for stand-alone BESS is 27% greater than solar-paired BESS's savings, indicating a lack of synergy between residential BESS and PV. Though both BESS types offset the same amount of on-peak consumption, the figure below shows the energy was valued differently depending on the system type.

For example, on-peak bill savings are 15% higher for the stand-alone BESS due to the electric rate's two-tiered energy charges. Without a PV system, 68% of summer consumption is billed at Tier 2 energy rates. In contrast, a PV-equipped residence's summer consumption is billed entirely at Tier 1 energy rates, resulting from PV's ability to keep monthly consumption below the Tier 2 thresholds. However, more costly Tier 2 rates impact both reductions (on-peak and off-peak) and increases (super off-peak) in stand-alone BESS's billed charges, so rate tiering has a negligible effect on *net* bill savings.

Residential BESS Annual Bill Savings Comparison



Factors Leading to Lack of Solar-Paired Synergy

Midday charging using solar energy is the primary contributor to the lower bill savings achieved by solar-paired BESS. Secondarily, minimum bill charges also erode the savings generated by solar-paired BESS.

Solar charging prevents the BESS from achieving weekday off-peak energy reductions, leaving on-peak reductions as the major energy arbitrage opportunity. Additionally, the energy arbitrage value between off-peak periods (when solar-paired BESS primarily charges) and on-peak periods (when solar-paired BESS primarily discharges) is 5 cents per kWh less than the arbitrage value between super off-peak and on-peak periods. Sacrificing an extra 5 cents per kWh of arbitrage value makes economic sense because charging solely from solar PV ensures eligibility for the investment tax credit, which has a net positive impact on *total* system economics (which considers bill savings *and* equipment installation costs). Nevertheless, a PV system worsens the BESS bill savings for the electric rates and systems modeled.

Moreover, the solar-paired BESS's limited energy arbitrage opportunities result in lower utilization of the battery, and it discharges 17% less energy throughout the year than stand-alone BESS.

Given that the residential federal ITC is scheduled to fully expire at the end of 2021, we also looked at a scenario where solar-paired BESS was not required to charge solely using solar energy. With the solar charging constraint removed, solar-paired BESS generates bill savings that are still 3% lower than stand-alone BESS due to incurring minimum bill charges. The insight is again that residential PV and BESS systems lack synergy, and customers seeking bill savings are likely to be indifferent toward solar-paired or stand-alone BESS after the federal ITC expires.

4 Conclusions

Our analysis of behind-the-meter battery storage systems in SDGE's service territory showed that non-residential systems have larger bill savings when paired with solar PV. Conversely, residential BESS does not show the same bill-saving synergies between PV and BESS systems.

Non-residential solar-paired BESS generates 50% more bill savings than stand-alone BESS because the PV system makes it easier to reduce on-peak demand using less stored energy, leaving extra stored energy to reduce non-coincident demand. The bill savings from residential solar-paired BESS are 21% lower than stand-alone BESS primarily because of the requirement to store midday energy from the PV system (for federal investment tax credit eligibility), and secondarily because minimum bill charges cancel out 10% of the solar-paired BESS's bill savings.

Historical SDGE customer adoption of BTM battery systems is at odds with the findings of our analysis. SDGE's BESS interconnection database indicates approximately 26% of currently installed non-residential BTM battery storage capacity is solar-paired, while 98% of residential BESS is solar-paired. Given that non-residential solar-paired BESS has higher bill savings and can be eligible for the federal ITC, one would expect solar-paired BESS to represent a higher percentage of customer adoption.

Historical adoption of residential BESS is puzzling for several reasons. Neither stand-alone nor solar-paired BESS shows a positive return on investment after considering installation costs, yet residential BESS account for roughly 42% of the total installed BTM battery storage capacity in SDGE's territory. Though the federal ITC makes the total system economics of solar-paired BESS more attractive than stand-alone BESS, the financial difference is too small to explain why 98% of residential systems are solar-paired. If residential customers are installing BESS as a form of backup power and are not focusing on bill savings, there are conventional options for backup power that have much lower installation costs.

We don't have definitive answers for why SDGE customers are making the BESS adoption choices they've made historically, but we offer several possibilities below.

Non-Residential

- Since PV-equipped buildings represent a small percentage of total non-residential premises, there are fewer retrofit opportunities for adding BESS to an existing PV system.
- Installing both solar PV and BESS might require more capital than investors are willing to spend.
- Customers who have adopted stand-alone BESS might have unique load shapes (compared with the prototypical shapes used in this study) that facilitate large demand reductions without PV.
- Owners of PV-equipped buildings might be satisfied with the bill savings generated solely from PV and don't feel that a storage system is warranted.
- PV might complicate the BESS operational control strategies, making it difficult for vendors to guarantee larger bill savings and federal ITC eligibility.

Residential

- Vendors are likely to focus on the paired installation and combined economics of PV plus BESS since PV's attractive economics compensate for the BESS's poor economics.
- Vendors might be uncertain of the true incremental economics of solar-paired BESS and may be over-selling the BESS's bill-reduction potential.

- Early PV adopters, perhaps having higher likelihood of being technology enthusiasts or environmentally friendly, might simply want a cutting-edge or low-carbon battery backup power system.

Though this report's focus is on bill savings rather than total system economics, it is worth noting that our analysis generally did not find residential BESS systems, whether stand-alone or solar-paired, to be cost-effective. Conversely, non-residential BESS systems showed potential for generating a positive rate of return. For a closer look at total system economics, we refer the reader to the Behind-the-Meter Battery Market Study.

Finally, the value proposition of BESS is heavily influenced by local electric rates, customer-specific demand profiles, and the configurations of the PV and BESS systems. As such, the takeaways provided here may not apply universally, but this analysis provides a useful case study that augments our understanding of the beneficial or detrimental interactions between behind-the-meter solar PV and battery systems in SDGE's territory.

5 Acknowledgements

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