

The Decarbonization Impact of Grid-Interactive Efficient Buildings – An Affordable Housing Use Case

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ABSTRACT

The paper discusses an approach to decarbonizing affordable housing using a combination of solar, energy storage, and load management (demand flexibility) by transforming the community into a Grid-Interactive Efficient Building (GEB). The community in Southern California employed a full set of decarbonization measures at the individual living unit level (mini-split heat pump HVAC, EnergyStar appliances, LED lighting) alongside community-scale 120kW Solar PV and 120kW/120kWh energy storage. The community supports low- and moderate-income residents with a significant portion of units allocated for previously homeless residents of Los Angeles County.

With electricity ratepayers in California being switched to Time of Use (TOU) rates, the need of this community to manage their electricity use and reduce their energy burden is imperative. In addition to solar, storage, and efficient electrification, the community also adopted a behavioral TOU energy management mechanism using a messaging platform. The project was able to achieve around a 9% reduction in total electricity use from just the behavioral energy management during the 4-9 pm peak TOU hours in summer 2021 compared to summer 2020. The net savings are expected to be higher as the battery was discharged during the 4-9 pm peak hours as well. In the Fall, the energy storage system was profiled to reduce the energy drawn from the grid during times of peak grid marginal carbon content (which is not coincident with peak TOU hours) to help further contribute to decarbonization. The collective set of measures are expected to provide for significant decarbonization potential for this community.

Introduction

The Electric Power Research Institute (EPRI) led an energy resource integration project using a combination of solar, energy storage, and load management (demand flexibility) at an affordable housing multifamily property in a disadvantaged community in Southern California. The project came at a significant moment in California history marked by the confluence of State of California policy and program initiatives advancing decarbonization, zero net energy, the multifamily segment, solar PV + storage, and equitable access to energy innovations and their economic and environmental benefits.¹ Furthermore, with the impending transition of all electricity ratepayers in California to Time-of-Use (TOU) rates, strategies to manage the

¹ Gas reduction landmark bill Assembly Bill (AB) 32, AB 693 and AB 2514, Senate Bill (SB) 32, SB 100 and SB 350 and the Long-Term Energy Efficiency Strategic Plan

electricity use and reduce the energy burden of disadvantaged communities was imperative. The primary objective of this project was to maximize the benefits of solar PV for a vulnerable population, while enabling grid flexibility and environmental benefits effectively to the entire rate base.

Key research questions included:

- What are the economics of community-scale solar + storage?
- How does it fit within the State’s policy goals?
- What are the early-stage technologies that overcome barriers of solar + storage in the field?
- What are some business models for utilities and policymakers to engage for customer and system-wide benefit?

Background

In 2017, EPRI began project development in partnership with an affordable housing developer/owner centered on one of their recently-completed multifamily properties. The property is a LEED-certified building adhering to transit oriented development principals, providing 61 affordable housing units for families, of which 31 are reserved for homeless populations, as designated by the County of L.A (LAHSA, 2017) in what is considered a disadvantaged community in Southern California. All of the property’s residents were on flat, discount electricity rates and would transition to TOU energy rates would, for the first time, vary by season and time of day. Table 1 highlights current and predicted TOU rates for residents of the host site. While these residents’ rates would remain discounted, variable rates could lead to greater overall bills, especially during peak summer times. In fact, in a 2017 pilot program to understand TOU impacts, the California Public Utilities Commission (CPUC) found that affordable rate-eligible customers in hot climates would experience higher total annual electricity costs under TOU pricing, resulting in \$20 - \$40 average monthly bill increases. Customers in Southern California were also generally found to be unlikely able to offset a significant portion of the bill increases by load shifting (Hawiger, 2017).

Table 1: Current and Predicted TOU Rates* for Affordable Rate-Eligible Customers

Current Rates (\$/kWh)	Time of Day	TOU Rates – Summer*	TOU Rates – Winter*
\$ 0.12305	Peak	\$0.3134	N/A
	Mid-Peak	\$0.1849	\$0.1317
	Off-Peak	\$0.1218	\$0.1152
	Super Off-Peak	N/A	\$0.0934

*Applies a 30 percent discount to rates to estimate impact of CARE discounts for residents only
Source: Southern California Edison, 2021.

Technology Overview

The property had deployed a full set of decarbonization measures (e.g., mini-split heat pump HVAC, EnergyStar appliances, LED lighting) at the individual living unit level. EPRI oversaw the design and installation of the solar, energy storage, and load management (demand flexibility) components, which comprised of two near identical 60 kW high efficiency bifacial solar PV arrays and 60 kW 120 kWh lithium-ion batteries at each housing building (Figure 1) with a demonstration of direct current (DC) distribution and appliances for common area loads, specifically 24V DC lighting and a four-ton DC-enabled variable refrigerant flow (VRF) system, at Building 2. In addition, the project also tested a battery system controls and behavioral demand response strategy, which included a TOU energy management mechanism for residents. The technology concepts are pictured in Figure 1 and 2 and further detailed in the subsequent sections.



Figure 1: Site Layout
Source: Google Maps, 2020.

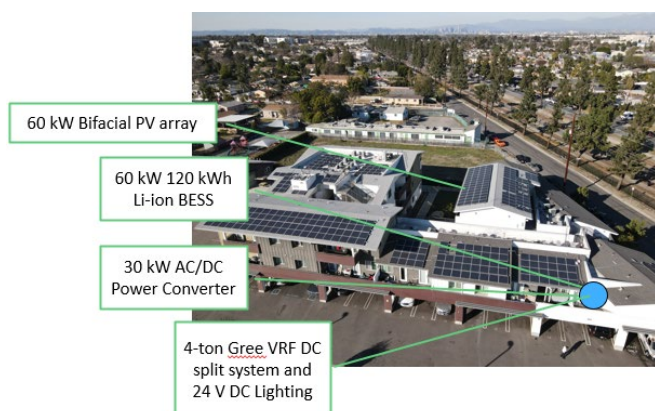


Figure 2: Building 2 View.
Source: Staten Solar, 2021

Installed Equipment and Results

Bifacial PV models were chosen to optimize the use of limited roof space, which is a common constraint in commercial and multifamily applications where roof space can be relatively sparse. By collecting energy from both the top and back of the modules, bifacial PV are expected to improve yield over mono-facial PV systems. Target efficiency for the project was 23%. 170 Canadian Solar CS3U 355-watt bifacial panels were paired with 60kW lithium ion batteries as shown in Figures 3 and 4.

A DC-coupled multiport inverter was selected partially because it fulfills California's Rule 21 Phase 1 mandates for grid supportive functions, which govern required "autonomous" functions that distributed energy resources with inverter-based interfaces must possess for utility interconnection. The inverter has three bi-directional ports (2 alternating current (AC) and 1 DC). An inverter, such as this one, allows individual control of storage and PV modules. It also saves conversion losses between solar PV and battery system charging without converting to AC. The roundtrip efficiency is 97%. Figure 4 depicts the installed inverters.



Figure 3: Bifacial PV Installation.
Source: EPRI, 2021.



Figure 4: Installed Inverters (Left) and Batteries (Right).
Source: EPRI, 2021.

The controls strategies employed the levers of the storage system controller as well as customer notifications through a behavioral DR messaging platform. The timed strategies were expected to reduce use and discharge batteries during TOU peak periods (summers, 4-9 PM) and peak EV system charging (9-10 PM), to charge batteries during periods of high solar output, discharge batteries during periods of high marginal carbon emissions of the California electric system (winter, 3-8 AM) and enroll residents in the Demand Responses Auction Market. The scenario implemented at the site takes a targeted approach by addressing greenhouse gas (GHG) reduction in the winter when they are at their highest and TOU rate mitigation in the summer when system peaks and high pricing is in effect, is depicted in Figure 5.

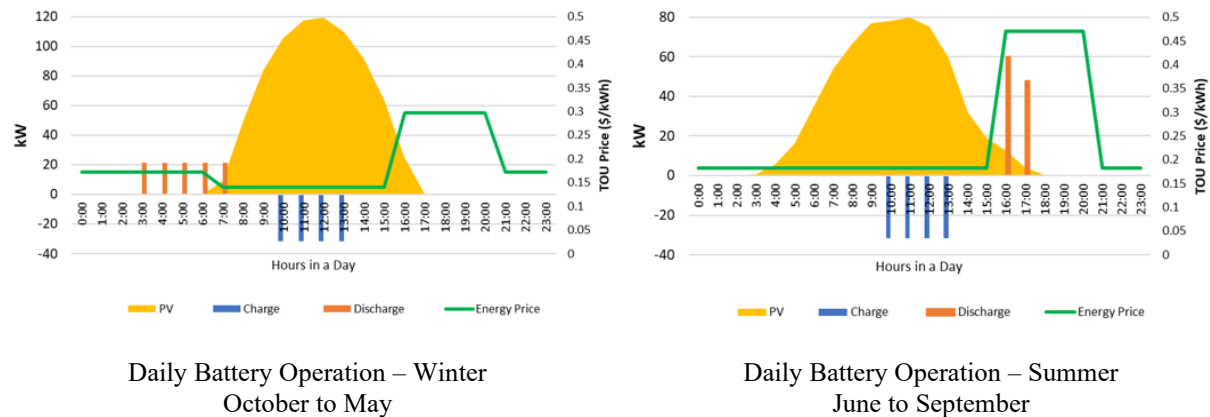


Figure 5: Controls Schedule
Source: EPRI, 2021.

EPRI worked with a residential demand aggregator to enroll residents into a customized behavioral demand response program that incorporated TOU-related messaging and behavioral energy savings tips into its day-ahead and day-of notifications. All of the project's energy savings and demand reductions are entirely the result of behavioral changes. Figure 6 depicts the enrolled residents' experience of the TOU behavioral DR program.

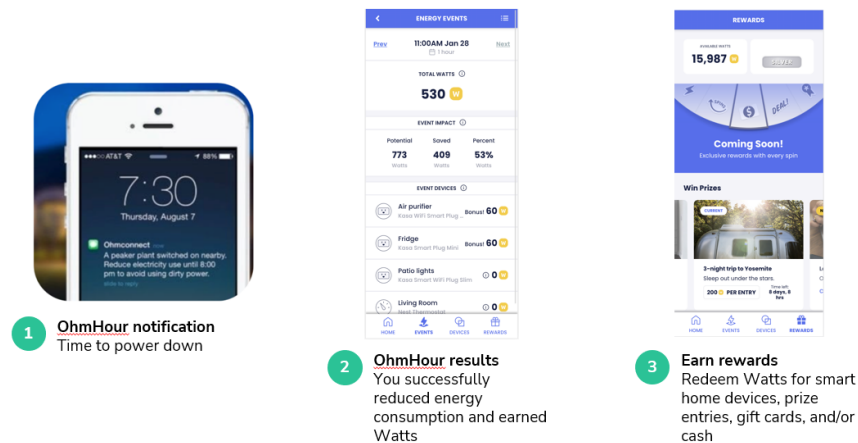
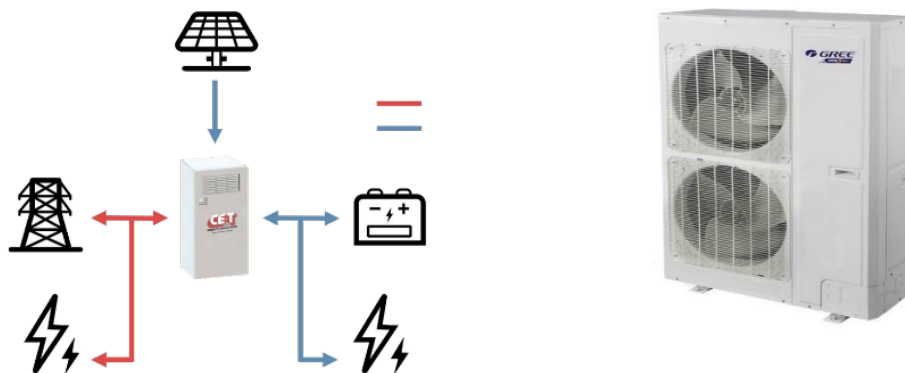


Figure 6: TOU Behavioral DR Customer Experience.
Source: Ohmconnect, 2020.

Figure 7 depicts a few of the components of the DC microgrid demonstration that was deployed as part of the project. Not pictured is a custom-designed source selector, or automatic transfer switch, that allowed for remote switching from AC to DC modes of operation for testing purposes. An estimated one-third of U.S. residential electric loads are native DC, and electric vehicles could increase this share. Residential applications have particularly high potential. This demonstration aimed to demonstrate how PV + battery storage + DC loads are naturally compatible with substantial savings potential in residential buildings relative to traditional AC distribution systems with compounding losses estimated to be as high as 33% (Pantano, 2016).



The CE+T Stabiliti 30C3 is a power conversion system or inverter that allows simultaneous DC and AC loads and multidirectional power flow.

The Gree VRF GMV-Y36WL/A-T(U) is a variable speed mini split heat pump that can work in native 100-380V DC but also in AC mode.



The Nextek Power Hub Driver (left) is a low voltage DC distribution system that converts 380VDC power to 24VDC to plug in Lamar DC lighting (right).

Figure 7: DC Distribution and Appliance Demonstration Components, Manufacturer Images
 Sources: CE+T, Gree, Nextek, Lamar, 2021.

Results and Lessons Learned

Bifacial PV Conversion Efficiency

This project demonstrated that, unless there is sufficient space on reflective flat roofs, dual sided PV (which is rated high efficiency) cannot deliver the full benefit on sloped roofs. The site has a mix of flat white reflective roofs and sloped dark asphalt roofs, requiring modules be installed at different tilts and azimuths (see Figure 8) with only four total maximum power point tracking (MPPT) channels and ground reflected irradiance (GRI) mismatch due to variable mounting arrangements. As noted by researchers at Sandia National Laboratories, bifacial modules may actually produce less power than equivalent mono-facial modules where mismatch is present and granular MPPT is not available (Riley, Stein and Carmignani, 2018). As a result, the installed bifacial PV array performed at 84% of modeled DC production and 78% of modeled AC production.



MODULE COUNT AND RATING PER ARRAY						
ARRAY	TYPE	MODULE TYPE	MODULE DIMENTIONS	MODULE RATING	AZIMUTH	TILT
ARRAY 1	ROOF TOP	LR6-72BP-355M	77.83" X 39.21" X 1.18"	355W	180	12
ARRAY 2	ROOF TOP	LR6-72BP-355M	77.83" X 39.21" X 1.18"	355W	180	5
ARRAY 3	ROOF TOP	LR6-72BP-355M	77.83" X 39.21" X 1.18"	355W	270	12
ARRAY 4	ROOF TOP	LR6-72BP-355M	77.83" X 39.21" X 1.18"	355W	90	12
ARRAY 5	ROOF TOP	LR6-72BP-355M	77.83" X 39.21" X 1.18"	355W	75	12

Figure 8: Building 2: Solar As-builts.
Source: Staten Solar, 2021.

Behavioral TOU Demand Response

Project partner Ohmconnect worked with EPRI to build out custom messaging and behavioral energy and demand reduction recommendations to prime residents for TOU rates. Roughly one-third of Willowbrook residents successfully enrolled in the behavioral TOU demand response program, a customized demand response aggregation program that bids behavioral demand reduction into the Demand Response Auction Market. Performance data suggests that residents actively engaged, and that monetary incentives and gamification mechanisms were motivating factors for participation. Sampled residents participated in at least 50% of DR events and saved up to 50% compared to their historic baseline. The project was able to achieve around a 9% reduction in total electricity use from just the behavioral energy management during the 4 to 9 PM peak pricing TOU hours in summer 2021 compared to summer 2020.

DC Microgrid Demonstration

The primary objective for the DC microgrid demonstration was to test the avoided conversion losses and the associated reduction in inverter capacity and cost by using DC power direct. As depicted in Figure 12, the solar + storage were configured to feed common area 24V DC lighting and a DC-enabled 4-ton VRF.

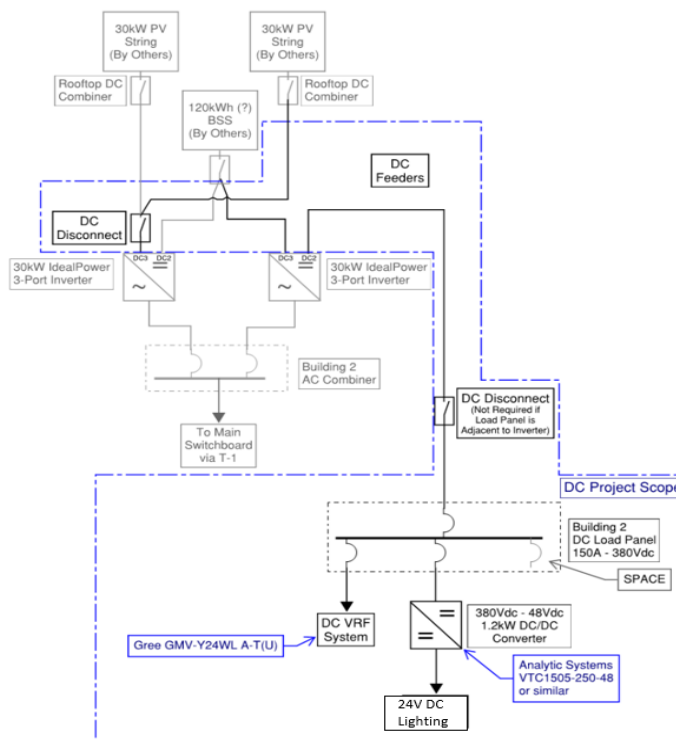


Figure 12: DC Demonstration Single Line Diagram

Source: EPRI

DC Lighting

Replacement of existing LED AC lighting fixtures, (49/42W 5500 lumens) with 24W 2600 lumens DC light fixtures resulted in a 3.6 % efficiency gain in terms of lumens per watt. While controls such as dimmers and occupancy sensors can further increase efficiency, those compatible with DC lighting with Underwriters Laboratories (UL) listings were not readily available, requiring EPRI to pursue a UL2108 UL 2108 Low Voltage Lighting System field evaluation in partnership with Nationally Recognized Testing Lab in order to meet the condition of the local permitting authority LA County. While DC lighting often uses low voltage cables for safety and ease of installation, cable losses are relatively high when low voltages are used. Cable losses were mitigated at Willowbrook by using a 250V DC lighting driver located as close as possible to the light fixture themselves, which are 24V DC. In conclusion, the primary challenges and industry opportunities identified during the DC lighting implementation are the need to explore expanding availability of 380V DC or higher voltage DC lighting for optimal efficiency as well as the need to establish availability of UL-listed DC lighting controls.



DC-Enabled HVAC

Due to lack of compatibility between the inverter and Gree VRF, a GFDI fault protection fuse blew. As a rectification plan, pictured in Figure 16, the outdoor unit control board was replaced, and the unit was connected and powered successfully directly to the solar. The source selector or automatic transfer switch was installed to enable remote switching from AC to DC modes of operation. A statistically significant DC versus AC performance comparison will require long-term alternate-day testing, which is ongoing. Unfortunately, the system has experienced technical difficulty, preventing its successful operation in DC mode.

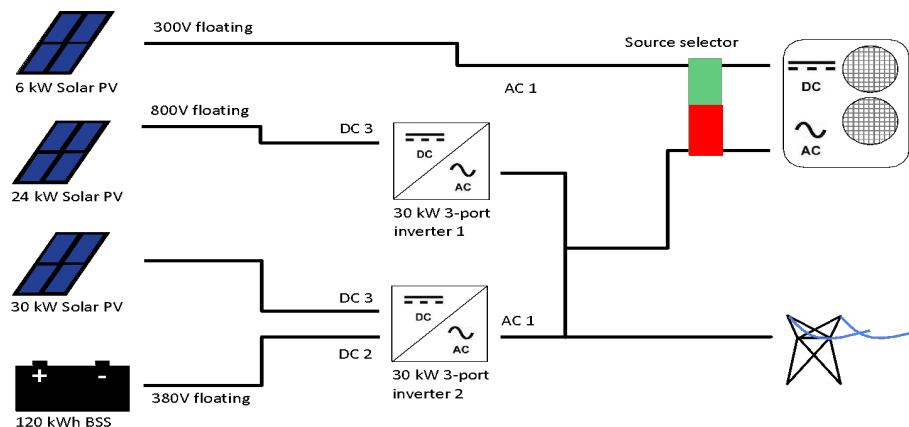


Figure 16: Installed Configuration in which 6kW Solar PV Connected Directly to Source Selector and VRF.

Overall Project Performance

The team compared pre- and post-installation building net energy profiles to evaluate the performance against original objectives of reducing use during TOU peak periods and peak EV system charging, solar balancing and reducing costs and GHG emissions and increasing participation in the Demand Response Auction market.

As depicted in Figure 9, in summer 2021, post-installation average daily energy performance peaked well before the 4 to 9 PM timeframe but was otherwise quite similar in trend compared to 2020. Load shifting was apparent during the 4 to 9 pm timeframe and before 12 PM with new peak around 2 PM. The reduction in energy use between June to September of 2020 and June to September 2021 was ~1.48 MWh. The net benefit to the community is significant reduction in energy burden. For society, it is in the reduction of Scope 1 and Scope 2 GHG emissions.

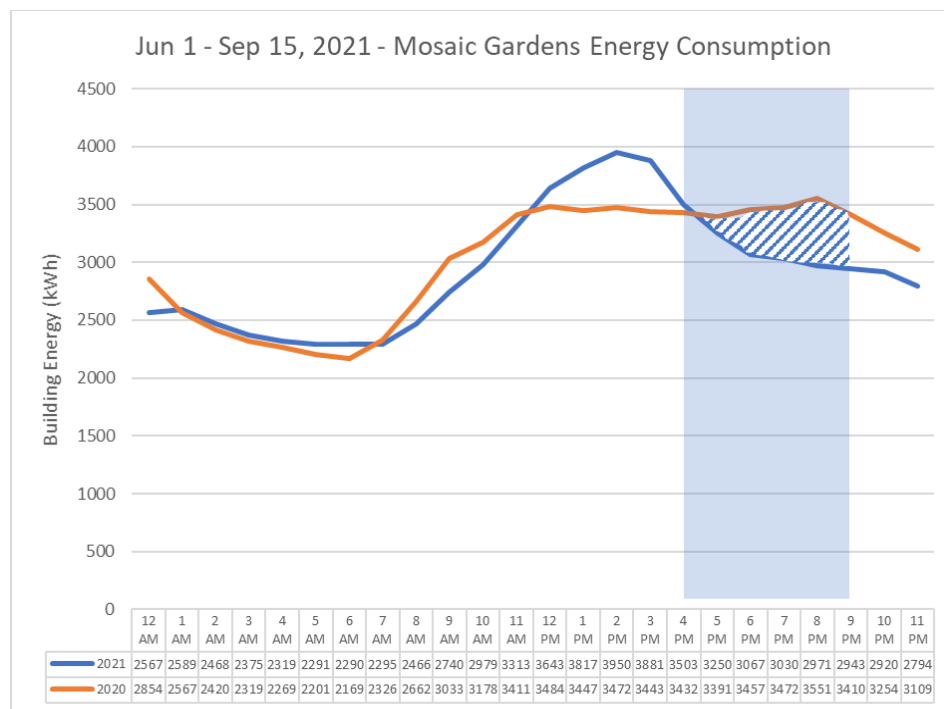


Figure 9: Comparison of Pre-(2020) to Post-Retrofit (2021)
Average Daily Energy Performance for June 1 to Sep. 15, 2021
Source: EPRI, 2021.

As depicted in Figure 10, energy consumption in Fall 2020 was higher almost throughout the day than Fall 2021. This downward shift in the entire load profile is more attributable to energy efficiency as opposed to signaling or TOU management. The summer load shifting pattern is not observed in the Fall. This is expected (especially after October 1) when the peak TOU rates are lower. Fall energy performance trends resemble the 2020 pattern except for early morning hours. Overall reduction in load (over 24 hours) in the Fall 2020 is 3.07 MWh over Fall 2021.

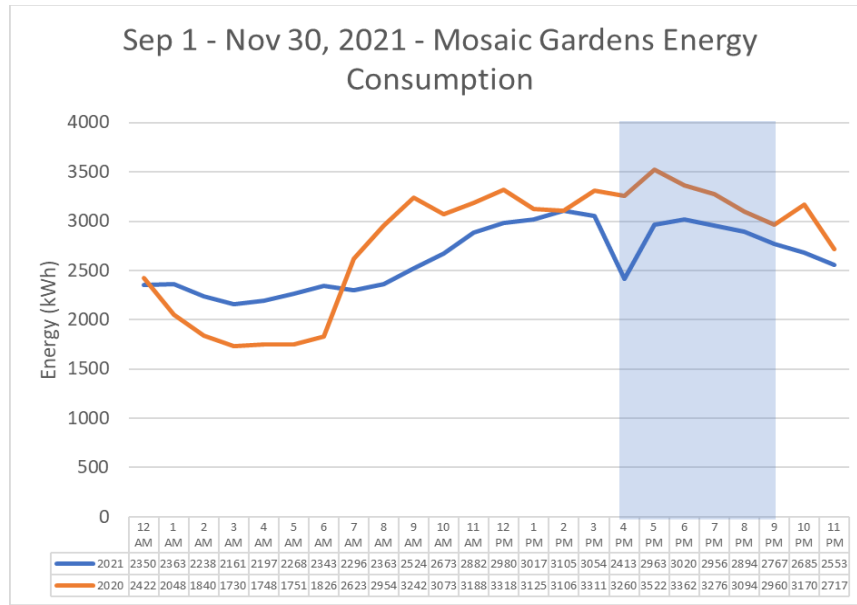


Figure 10: Comparison of Pre-retrofit (2020) to Post-retrofit (2021)
Average Daily Energy Performance for September 1- November 30, 2021
Source: EPRI, 2021.

As depicted in Figure 11, energy in Winter 2020 was higher almost throughout the day except for early morning. This downward shift in the entire load profile is more attributable to energy efficiency as opposed to signaling or TOU management. There was a significant reduction in peak energy use overall ~ 19.6% with the elimination of a peak in early AM hours. There was also a significant reduction in peak energy use of ~ 16% during the 4 to 9pm timeframe. Overall reduction in load (over 24 hours) in the Winter is 9.7 MWh and 2.9 MWh during the 4 to 9 PM timeframe. This corresponds to a 11% reduction in energy use over 24 hours and 13% during 4 to 9 PM timeframe.

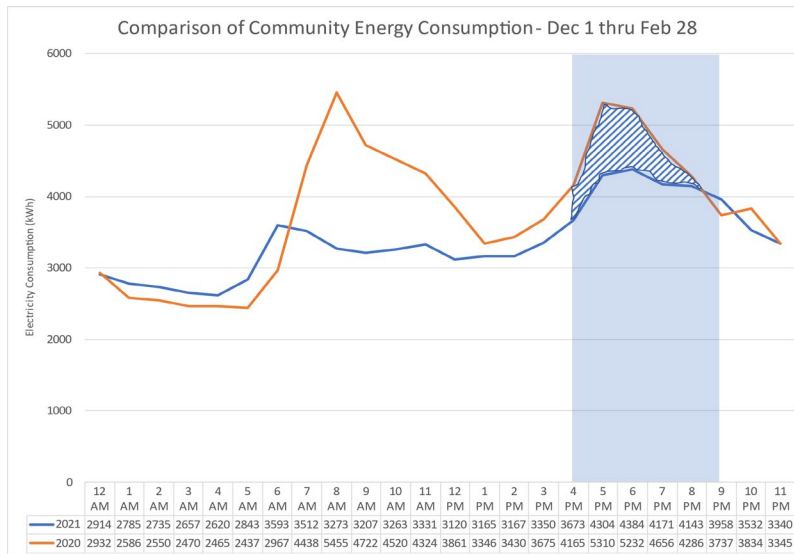


Figure 11: Comparison of Pre-Retrofit (2020) to Post-Retrofit (2021)
Average Energy Performance for December 1, 2021 to Feb 28, 2022
Source: EPRI, 2021

Cost-Benefit Analysis

Table 2 depicts the installed costs associated with the solar + storage scope, the only monetizable aspect is the utility bill savings under a TOU rate scenario and net energy metering. The net present value for the implemented scenario under the parameters in Table 2 was approximately - \$500K, suggesting negative cash flow and a poor investment. Among the project recommendations are improvement of the monetization potential from the carbon reduction and grid services benefits.

Table 2: Cost Benefit Analysis

Item	Cost	Parameter	Value
PV System Cost	\$132,775	Inflation	1.5%
Battery Cost	\$109,500	Discount Rate	7%
Controller & Software Cost	\$31,350	Analysis Horizon	10 years
Labor Cost	\$198,345	BESS & PV Lifetime	10 years
Equipment Cost	\$64,000		
Design & Construction Cost	\$70,030		
Miscellaneous Cost	\$36,000		
Total Cost	\$642,000		

Source: EPRI, 2021

Lessons Learned

Implementation of this project revealed a number of lessons learned.

There is a significant lift for property owners to conduct solar and storage projects: Most low-income housing is funded through tax credit financing with multiple investors. The affordable housing owner site host had five investors and one in particular had significant questions as to how the solar and storage could negatively impact the property (e.g., leaks). This type of negotiation takes a great amount of time, and thus becomes a monetary burden for the property owner that must be factored in new projects in low-income housing.

Economics of solar + storage for low-income communities is nascent/non-existent with current electric rates: The current virtual net energy metering (VNEM) rate structure means that the benefits of solar accrue mainly to the tenants. The Solar on Multifamily Affordable Housing (SOMAH) program, which also influenced the project design, effectively prevents the landlord from charging the tenants for the benefits of solar, which means that the property owners have to justify solar based entirely on the common area usage. In many cases, common area usage is very limited (in this case only 10,000 kWh a year), which means that property owners, when

leasing solar, cannot cover the lease payments. Energy storage also faces challenges. Without time differentiated tariffs, storage operation does not save cost to the tenants or the property owner. This means that the main benefit to the customer is improved resiliency, which is a luxury for most affordable housing property owners. Residents are expected to move to a TOU rate in 2022, which may slightly improve the value proposition.

Permitting and interconnection is still a challenge, but there are emerging solutions: This project was unique since it involved a DC-side connection of solar and storage with a single inverter. Completing the permitting process required a significant amount of administrative effort with the county of Los Angeles, as they were unfamiliar with a DC side connection. It was also difficult to obtain SCE approval, but it was enabled by prior work the vendor had completed with PG&E on a software-based monitoring solution for non-export Rule 21 interconnect. These projects have to budget a significant amount of time for interconnection. They also must account for how the property owner gets compensated for the time while the solar is not operational waiting for interconnects (since they have Power Purchase Agreement payments)

Integration of solar, storage, and loads (DR) is not as easy as it seems on paper: Most demonstrations of load aggregation use “preferred” products (i.e., products that have been tested as interoperable in a lab setting). However, in the field, customer end uses are primarily designed for meeting customer needs and chosen by the contractor, builder, or customer. This means that the systems in the field are not necessarily compatible with aggregation platforms, especially if the products do not have open interfaces to equipment. An example of this was the relatively new Carrier wired thermostats, which were installed by the HVAC contractor and are not open interface. These thermostats were not compatible with the controls platform and limited the scope of the controllable loads.

DC-Coupling

The DC-coupling aspects of the scope were, perhaps, the most challenging emerging technology component of the project. DC coupling between PV and storage is beneficial for interconnection as it limits total connected inverter kW, even though metering and control details are still a work-in-progress. DC coupling does not necessarily mitigate conversion losses because bridging various voltage requirements from appliances to EV chargers mean that conversion is required anyway. Codes and standards also limit DC voltages that may be used, which limits the benefits available from DC utilization -- this is not a recommendation to use HVDC in homes since DC fault behavior is not fully documented or mitigated. DC coupling may introduce new issues such as common mode noise, ripple, and negative impedance instability – coupling converters at different voltages will likely result in unintended consequences especially where manufacturers do not coordinate. Use of proprietary, low-volume hardware creates future risk of not being able to replace infrastructure. This is an emerging market with a classic chicken or egg problem.

Recommendations and Benefits

Recommendations for advancing market uptake are based on actions that can be taken by policy and program administrators, which are detailed in Table 3 below. Additionally, Table 4 presents the estimated project benefits.

Table 3: Recommendations

Solar	Offer workforce training for solar technicians on conducting installations for roof constrained commercial and multifamily applications, addressing advanced solar technology, modeling, proper siting, bifacial and use of module level power electronics for optimization
DC-Coupling	Promote updates to the National Electrical Code and building codes for general utilization of higher DC voltages.
	For metering and tariff compliance, inverter metering and controls can be used to ensure net energy metering integrity.
	Convene a manufacturing consortium for establishing common standards for DC utilization.
	Make incentives available to DC equipment manufacturers to expand availability of DC equipment, such as 380V DC or higher voltage DC lighting for optimal efficiency as well as UL-listed DC lighting controls.
	Lab testing to simulate integrated systems and close monitoring in the field of DC-coupled systems upon commissioning. This is important for addressing the common power quality issues with multiport inverter systems.
Economics	Improve customer monetization strategies for GHG reduction, net peak load reduction and resiliency, especially in cases where there are clear, overlapping stakeholder benefits and alignment with state policy
Community Engagement	Consult a resident engagement coordinator with social service/welfare background for engaging with affordable housing residents and facilitating administrative and technology requirements. Offer simple and straightforward requests with cash incentives for fulfilling those requests.
	Establish buy-in by critical stakeholders early in the project planning process including lenders for tax credit financed properties
	Ensure warranties and Operations & Maintenance (O&M) agreements are sufficient and meet stakeholder needs before installing systems

Table 4: Benefits

Lowered Costs	Potential for a bill reduction of \$253 million for California's low-income households.
Increased Reliability	Reduced evening demand by more than 8.6% during TOU peak periods from battery and 9% reduction from behavioral demand response.
Economic Development	This type of work could be scaled to significant job growth within the proper policy and incentive environment; Reduction of bills and greater disposable income for affordable housing residents and operator
Environmental Safety	Potential for statewide CO2 reduction over 83,000 metric tons per year.
Public Health	Reduction in air pollution and greater resilience through DC demonstration, which could help vulnerable populations in need of continuous power to operate medical devices during an outage.
Consumer Appeal	Enhancement of comfort and affordability of a LEED certified urban in-fill, mixed use and transit-oriented property for low-income disadvantaged community community
Energy Security	Reducing the need to build power plants and create consistent power for low-income disadvantaged community; technology transfer to affordable housing developer portfolio.

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