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U.S. DEPARTMENT OF ENERGY

Behind-the-Meter Solar+Storage:

Market data and trends

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ENERGY TECHNOLOGIES AREA | ENERGY ANALYSIS AND ENVIRONMENTAL IMPACTS DIVISION

Report Overview

Provides a data-driven overview and analysis of market trends for grid-connected residential and non-residential behind-the-meter solar+storage

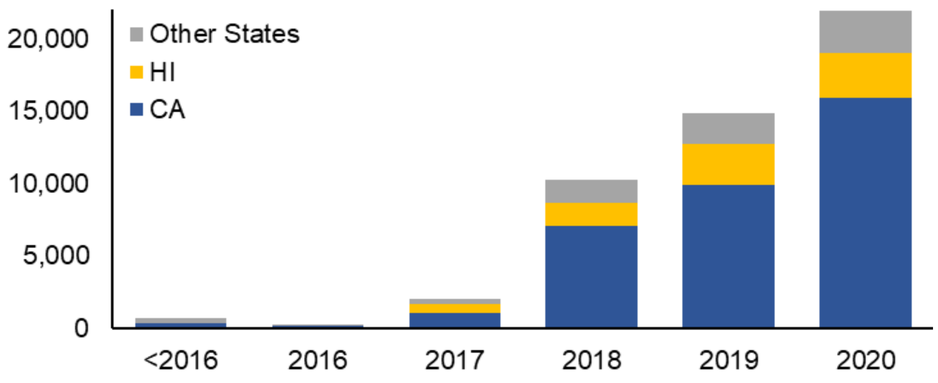
- **Deployment trends:** Temporal trends and differences across states, utilities, and zip codes; customer segmentation details; co-installs vs. retrofits
- **System characteristics:** System sizing, battery manufacturer shares
- **Installer market characteristics:** Uptake of storage among PV installers, depth of installer market for PV+storage, installer market shares, installer-level attachment rates
- **Installed prices:** Focusing on the price “premium” for adding storage to BTM solar; temporal trends and differences across installers and technologies; both installed and quoted projects
- **Customer financial value:** Indicative analyses of utility bill savings and other financial benefits from adding storage to solar, across several key markets
- **Customer resilience value:** Indicative analyses of residential solar+storage backup power capabilities, evaluated in terms of the percentage of daily load served

Data Sources and Sample

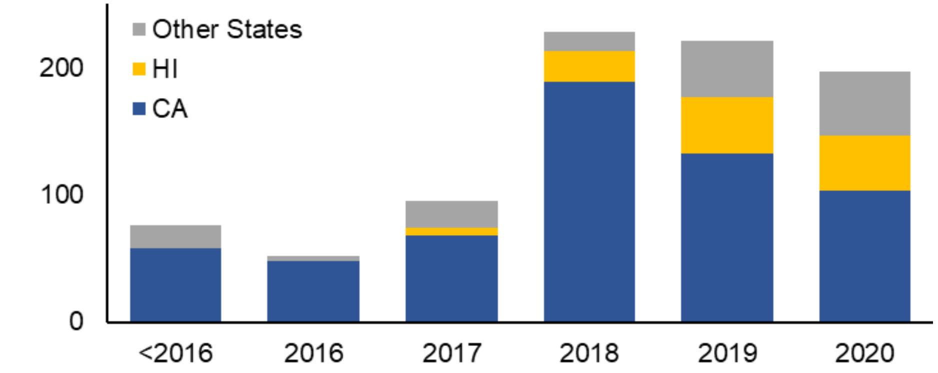
- **Report relies primarily on Berkeley Lab's *Tracking the Sun* dataset**
  - Project-level data provided by utilities, state agencies, and other program administrators
  - Data on paired systems includes a variety of system attributes (solar and storage sizing, make & model, installer, pricing, etc.)
  - Data completeness varies by data provider/state
- **Consists of roughly 50,000 paired residential and 1,000 non-residential PV+storage systems through 2020**
  - Covers ~90% of all paired residential systems and 90% of paired non-residential PV capacity installed through 2020
  - Dominated by CA and HI, consistent with the broader market
- **Installed pricing trends also include supplementary data from EnergySage on quotes for paired systems**

Primary Data Sample*

Residential Sample Size (# of paired systems)



Non-Residential Sample Size (# of paired systems)



** See Appendix for tabular summary by state and additional details on underlying data sources*

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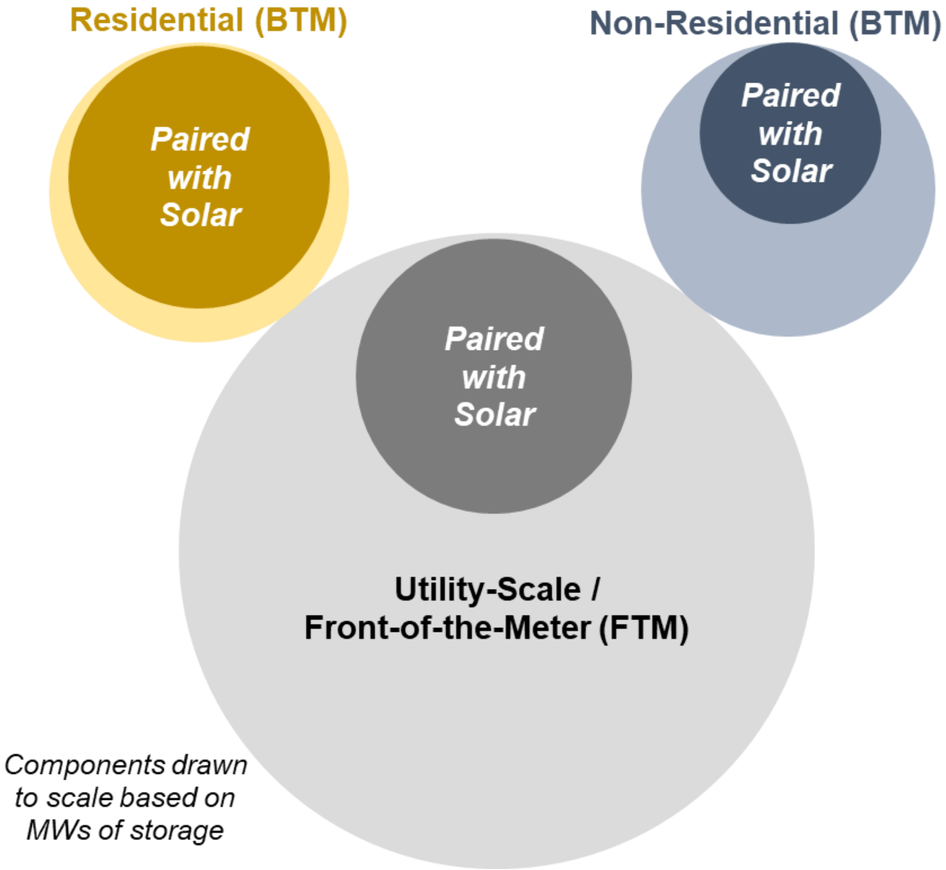
Deployment Trends

Positioning BTM Solar+Storage within the Broader U.S. Battery Storage Market

Total U.S. Electric Power Sector Battery Storage Capacity Installed through 2020



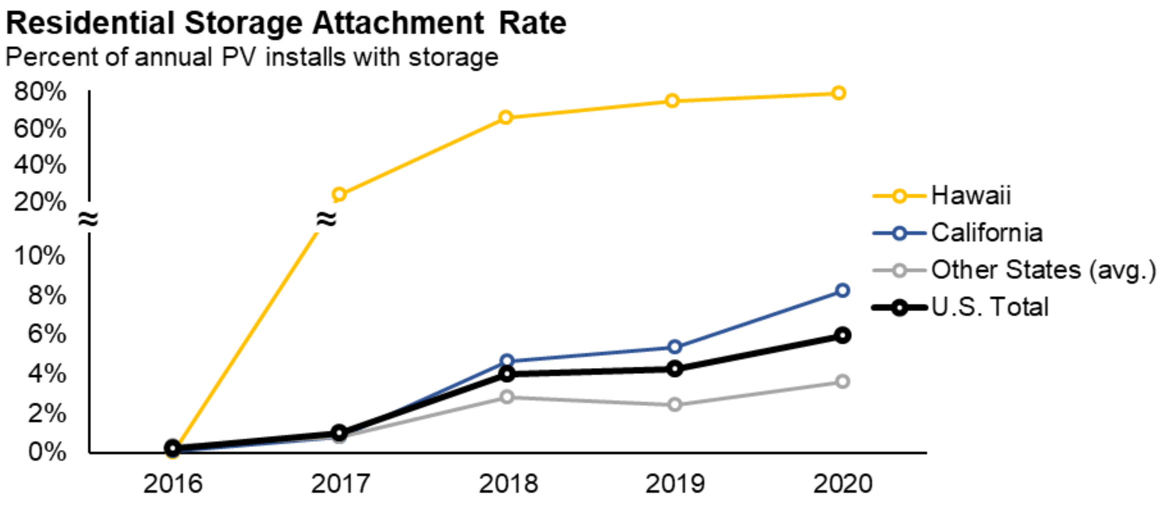
Data Sources: EIA, Wood Mackenzie, LBNL.

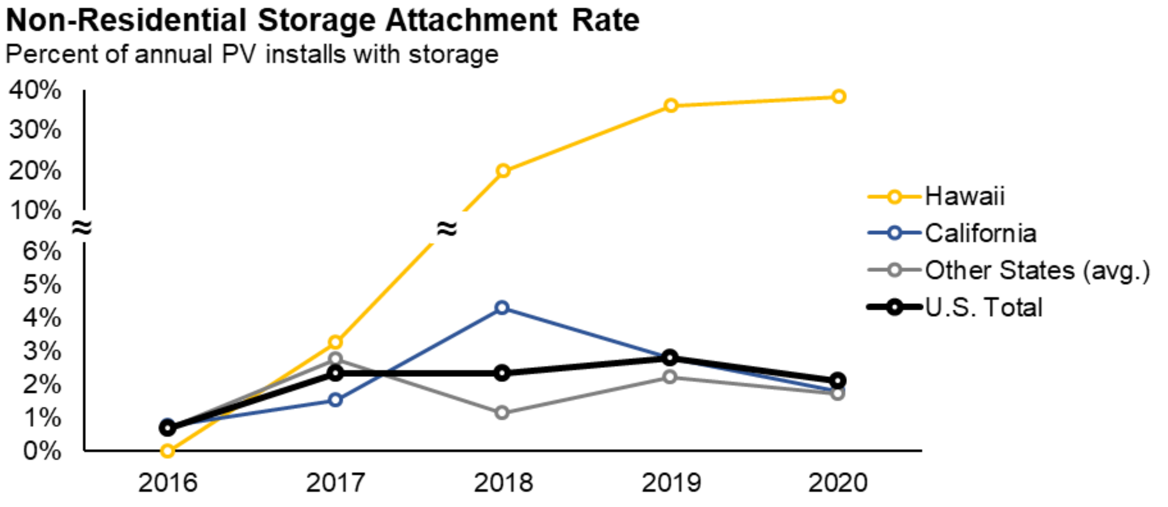
Out of the total 3200 MW of U.S. battery storage capacity installed through 2020

- Roughly 1,000 MW (30%) is BTM, and of that, 550 MW is paired with solar (the subject of this report)
- The vast majority (80%) of residential storage is paired with solar, driven by ITC rules, NEM reforms, and resilience considerations
- In contrast, most non-residential storage is installed on a stand-alone basis, presumably for demand-charge management; roughly 40% is paired with solar
- For reference, roughly 420 MW (19%) of all utility-scale/front-of-the-meter storage capacity is paired with solar

Storage Attachment Rates over Time

Percent of PV installs each year that include storage

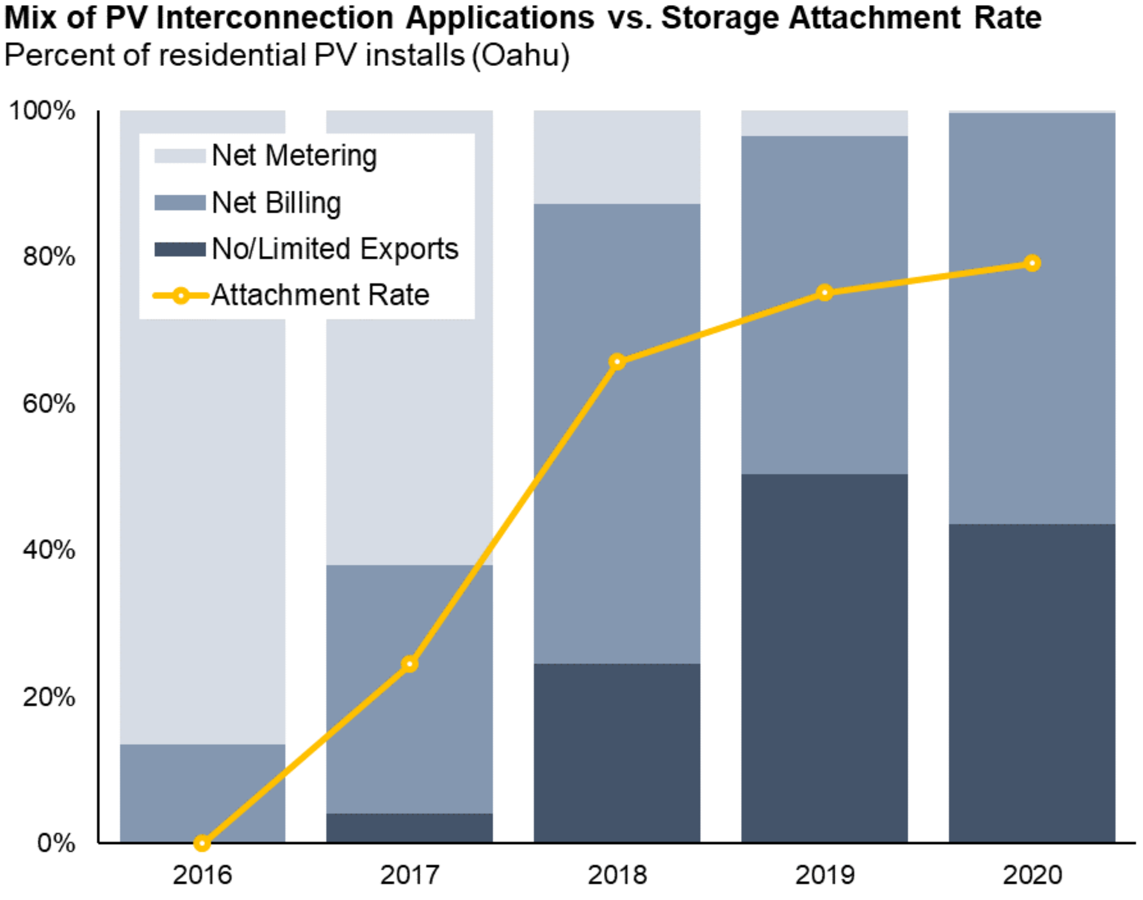




- Hawaii has, by far, the highest storage attachment rates of any state (80% residential and 40% non-residential in 2020), driven by net metering reforms that incentivize self-consumption
- California falls in at a distant second (8% and 2%, respectively, for res. and non-res. in 2020); driven mostly by incentives and wildfire resilience issues
- Attachments rates outside of CA and HI are generally lower, though some utilities have seen attachment rates in the 10-20% range (e.g., Salt River Project in AZ, Puget Sound Energy in WA)
- In general, residential attachment rates have been rising over time; non-residential trends are uneven, but in aggregate have been fairly flat
- In 2020, U.S. total residential attachment rose to 6%, while non-residential rates remained at 2%

Notes: Hawaii attachment rates are based on data for Oahu only. The averages shown for "Other States" are based on all states in the sample with available data. U.S. Totals are estimated by extrapolating to the out-of-sample portion of the U.S. market by assuming the same the attachment rate as for Other States.

Hawaii Paired PV+Storage and NEM Reforms



Notes: Data on the mix of PV tariff selections is based on the Hawaiian Electric's quarterly compliance filings summarizing the Company's weekly interconnection reports. For the purpose of this figure, Net Metering includes only the legacy Net Energy Metering tariff; Net Billing includes the Customer Grid Supply and Customer Grid Supply Plus tariff options; while No/Limited Exports includes the Customer Self Supply, Smart Export, and Net Energy Metering Plus tariff options (the latter of which is available only for expansions to existing net metering projects that have no exports).

- Hawaii has been transitioning away from net energy metering (NEM) via a series of successor tariffs introduced over the past ~5 years
- These include net billing tariffs that provide reduced compensation for grid exports, as well as tariffs that prohibit or limit grid exports—both of which incentivize pairing with storage
- Interconnections under the legacy net metering program phased out as wait-listed projects were installed or fell out of the queue
- Rising storage attachment rates mirror the market's migration away from NEM
- Presumably all (or virtually all) customers on tariff options that prohibit grid exports are installing paired systems, while more than half of those on net billing tariffs appear to be doing so

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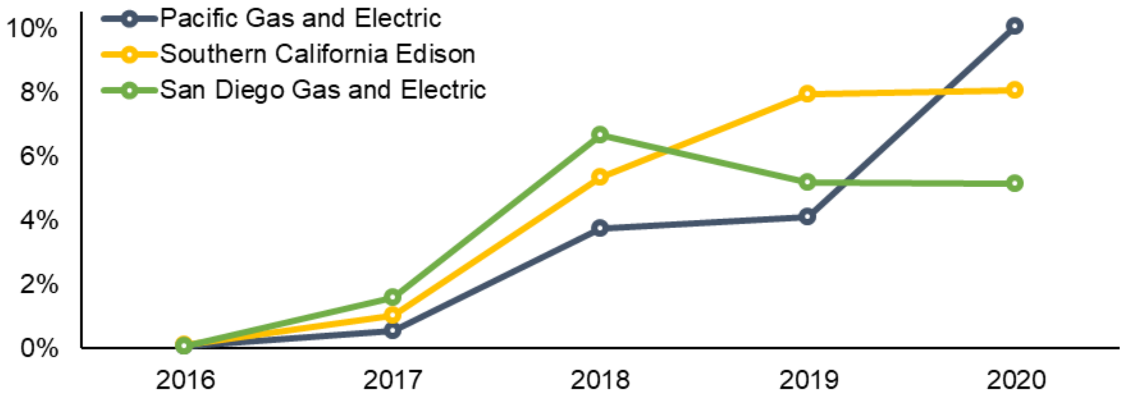
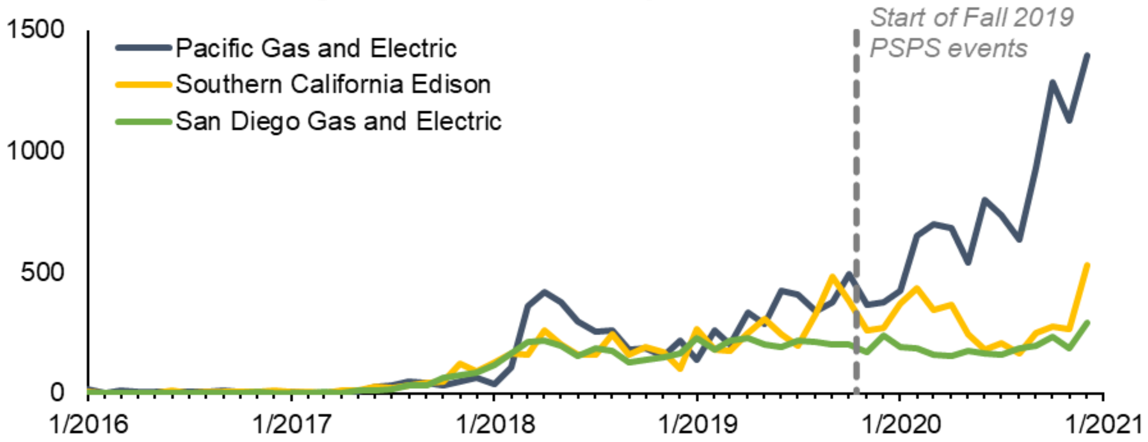
CA Residential Paired PV+Storage Deployment by Utility

Residential Storage Attachment Rates
Percent of Annual PV Installs with Storage



Residential PV+Storage Interconnections by Month



- Market driven by combination of long-standing incentive program and more recent reliability-related concerns in the wake of wildfires and Public Safety Power Shutoff (PSPS) events
- PG&E’s service territory saw a sharp uptick in 2020 in both storage attachment rates (top figure) and the absolute number of paired PV+storage interconnections (bottom figure), compared to trends for the state’s other investor-owned utilities
- Likely prompted in part by the Fall 2019 PSPS events, which primarily affected PG&E customers
- In addition, SGIP introduced much higher incentives for low-income customers in areas with high wildfire risk or that experienced multiple PSPS events (though those represented a small share of all paired SGIP systems installed in 2020)

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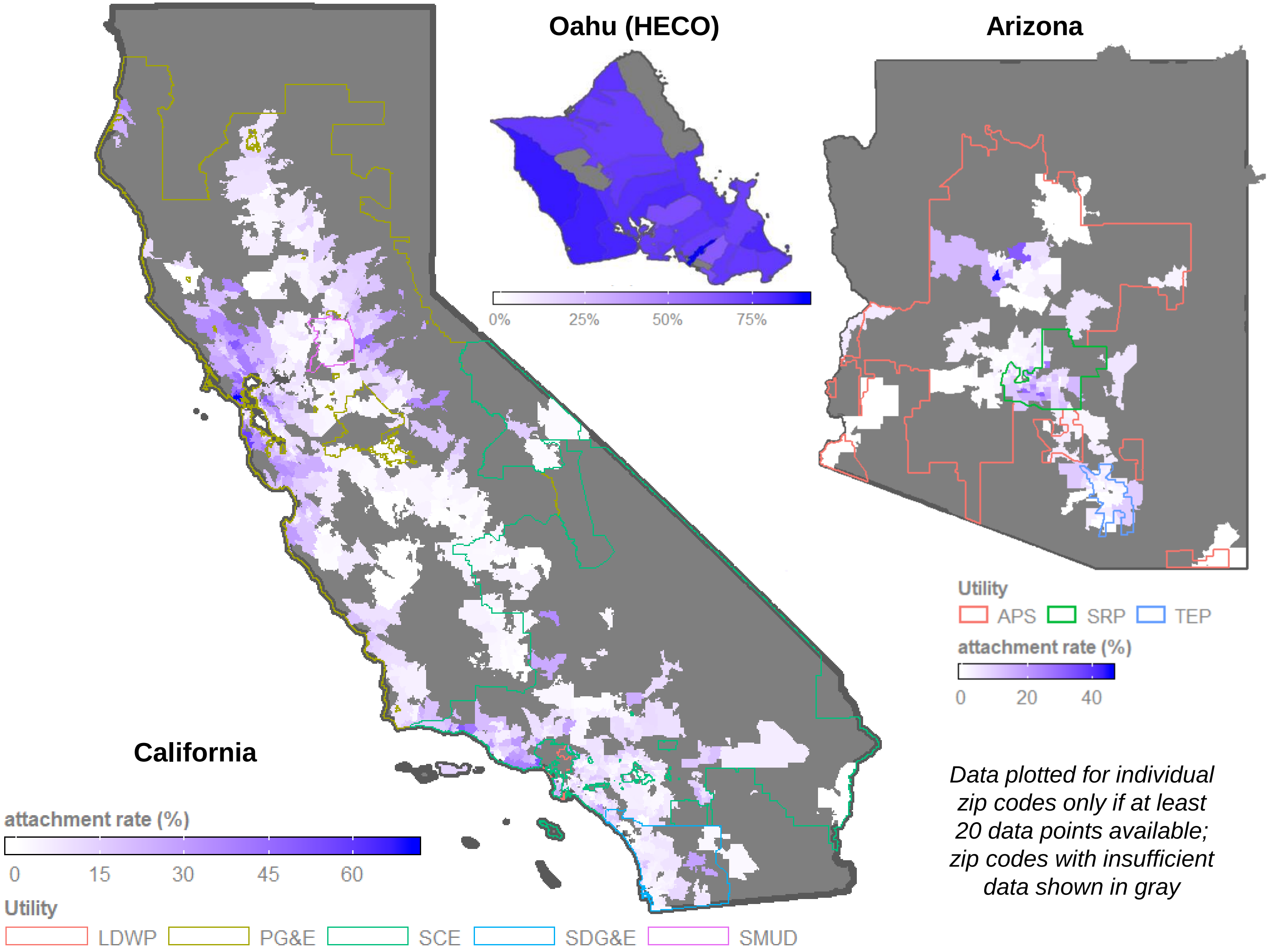
Zip-Code Level Residential Attachment Rates (2020)



Data plotted for individual zip codes only if at least 20 data points available; zip codes with insufficient data shown in gray

California: Attachment rates vary widely across zips, from 0-70%

- Higher rates in areas of Northern California impacted by wildfires and PSPS events
- Demographics no doubt also play a role: 9 of the top-10 zips are in affluent communities (Marin County, Malibu, other coastal towns)

Hawaii: Attachment rates uniformly high (64-90% across zips)

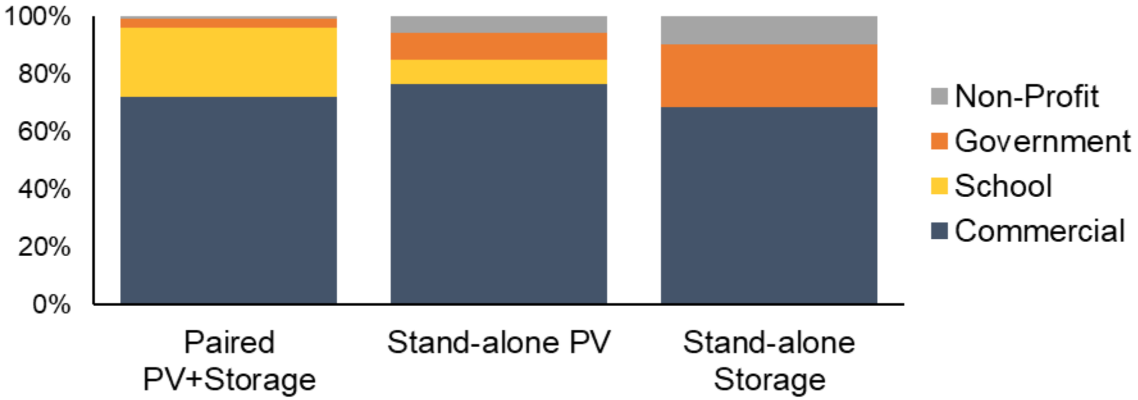
Arizona: Attachment rates from 0-45% across zip codes

- High attachments rates across SRP's service territory: storage rebates and rate reforms for solar customers that encourage storage
- The two highest attachment rates are in APS's territory; most of those systems were installed through a partnership between Sonnen and a large housing developer

Customer Segmentation Details

Residential-Adopter Median Incomes: Paired vs. Stand-alone PV*
Percent of Area Median Income (2019 systems)

Non-Residential Customer Segmentation (California)
Percent of non-res. BTM storage systems (2016-2020 installs)



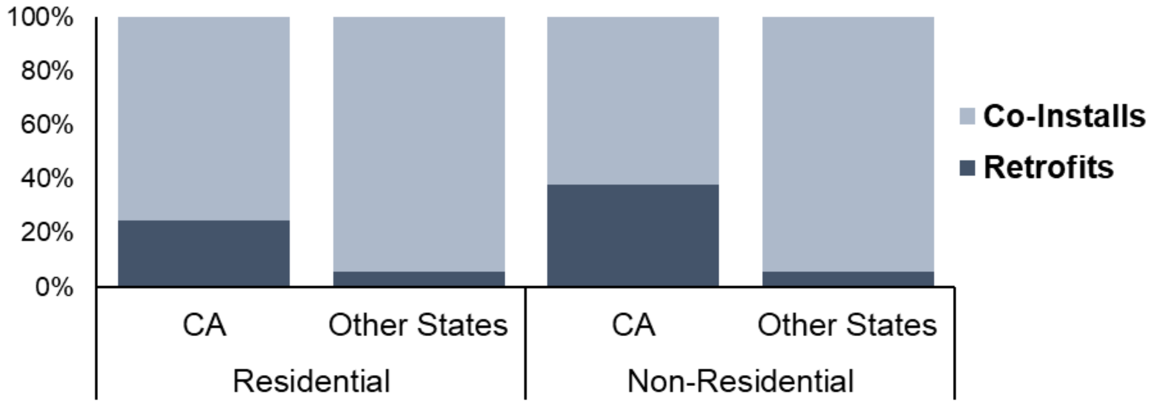
- Residential paired PV+storage adopters generally have higher incomes than stand-alone PV adopters (based on 2019 data from a separate Berkeley Lab report*)
- For example, in CA, paired PV+storage adopters had median incomes 66% higher than their Area Median Income, while stand-alone PV adopter incomes were 41% higher
- Within the non-residential sector, for-profit commercial entities comprise the bulk (70%) of all paired non-residential systems, similar to their share of stand-alone PV
- Schools make up a notably larger share (25%) of paired PV+storage systems than they do for stand-alone PV (8%), reflecting a unique resilience value and relatively large loads

*See *Residential Solar-Adopter Income and Demographic Trends: 2021 Update*

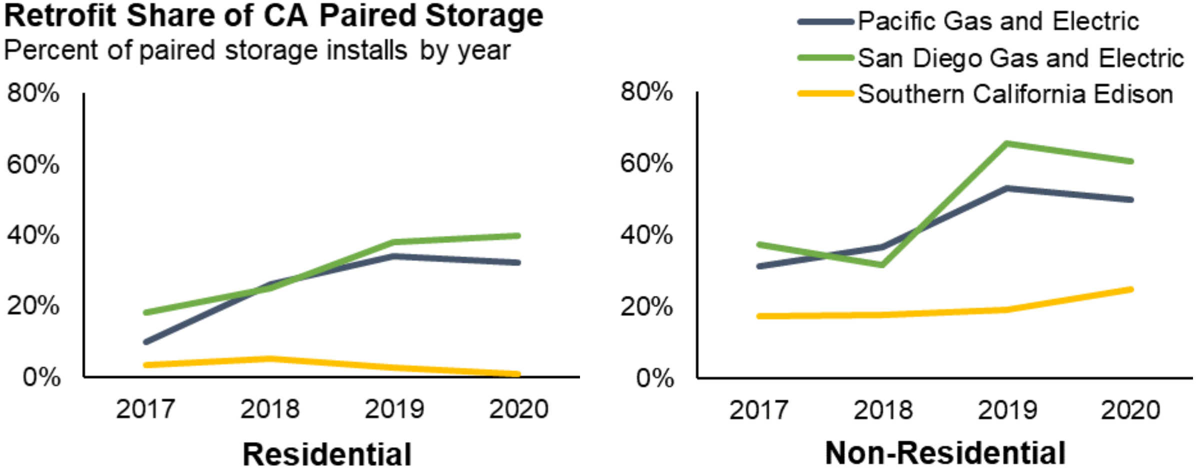
Storage Retrofits to Existing PV

Can get missed when focusing only on attachment rates / co-installs

Retrofits vs. Co-Installs:
Percent of paired storage systems (cumulative through 2020)



Retrofit Share of CA Paired Storage
Percent of paired storage installs by year



- A significant portion of paired systems in California consist of storage retrofits to existing PV systems: **25%** and **38%** of all paired residential and non-res. systems, respectively
- Outside of CA, retrofits constitute a much smaller share of the paired PV+storage market
- The retrofit share in CA has been increasing over time, especially among non-residential systems, and is much larger for PG&E and SDG&E
- Storage retrofits are being added to PV systems of widely varying vintage, though typically to systems 1-3 years old
- In about 10% of storage retrofits, additional PV capacity is being added as well

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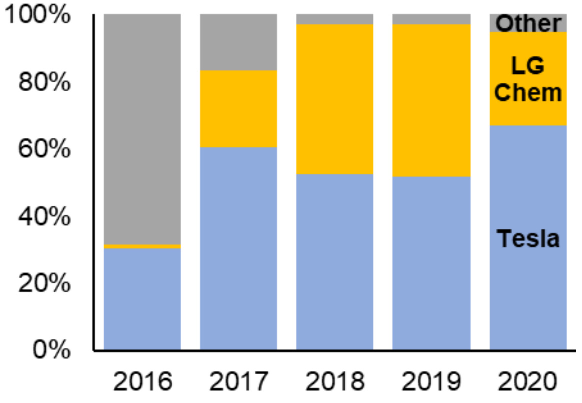
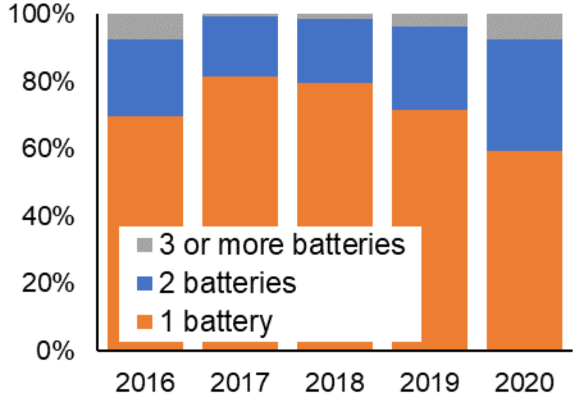
System Technical Characteristics

Residential PV+Storage System Characteristics

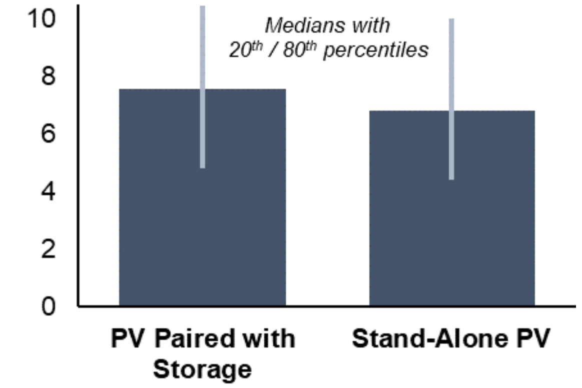
Storage Manufacturer Share
Percent of paired systems



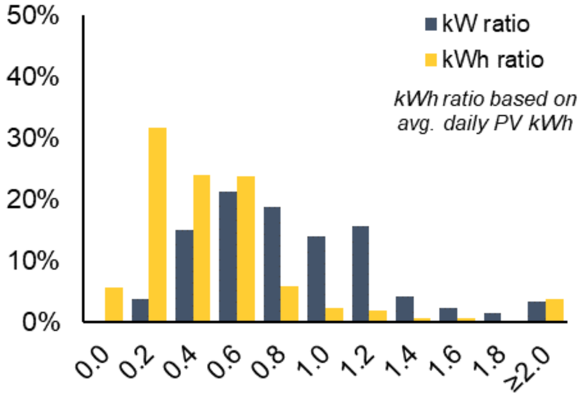
Number of Batteries per System
Percent of paired systems



PV System Sizes (kW_{DC})
Paired vs. stand-alone PV installed in 2020



Storage-to-PV Size Ratios
Percent of paired systems installed in 2020



- Market dominated by two storage products:
  - Tesla Powerwall: 5 kW / 13.5 kWh, (2.7-hr. duration)
  - LG Chem RESU 10H: 5 kW / 9.3 kWh (1.9-hr. duration)
- Most residential systems consist of a single Powerwall or RESU 10H, though larger (>5 kW) systems have become more common (40% of the market in 2020)
- PV systems paired with storage tend to be slightly larger than stand-alone systems (roughly 1 kW larger, in the median case)
- Given typical storage and PV sizing in paired applications, storage-to-PV kW ratios generally range from 0.6-1.2, while kWh ratios (the fraction of daily PV generation that can be stored) generally range from 0.3-0.8

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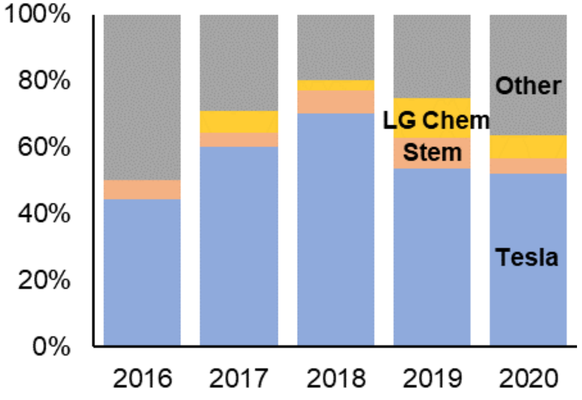
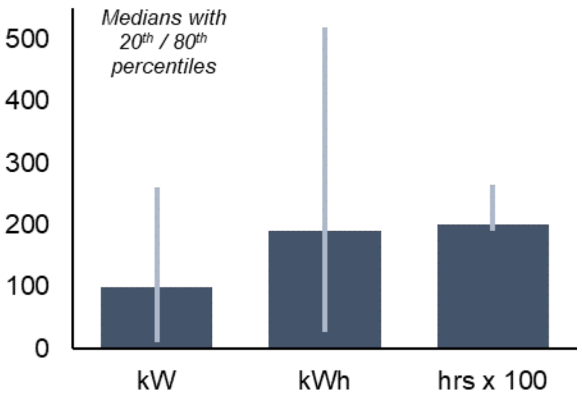
Non-Residential PV+Storage System Characteristics

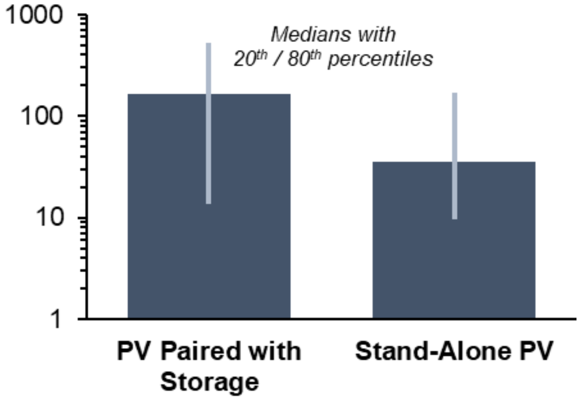
Storage Manufacturer Share
Percent of paired systems



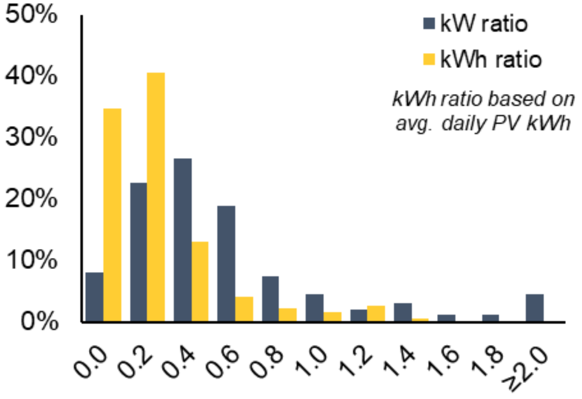
Non-Residential Storage Sizes
In paired systems installed 2018-2020



PV System Sizes (kW_{DC})
Paired vs. stand-alone PV installed in 2018-20



Storage-to-PV Size Ratios
Percent of paired systems installed 2018-2020



- The paired non-residential market has had more diversity among storage manufacturers than residential, though Tesla still dominates
  - Though not shown, Stem historically comprised a large share of *stand-alone* non-residential storage systems
- Storage sizing in paired applications ranges widely, but median values are 100 kW and 200 kWh; most are ~2-hour batteries
- PV systems in paired applications are generally much larger than stand-alone systems (a median PV system size of 200 kW for paired vs. 40 kW for stand-alone PV)
- Storage-to-PV size ratios are smaller than in residential applications: typically with kW ratios of 0.3-0.9 and kWh ratios of 0.1-0.4

Notes: Most of the figures on this slide aggregate non-residential installs over the 2018-2020 period, due to small sample sizes

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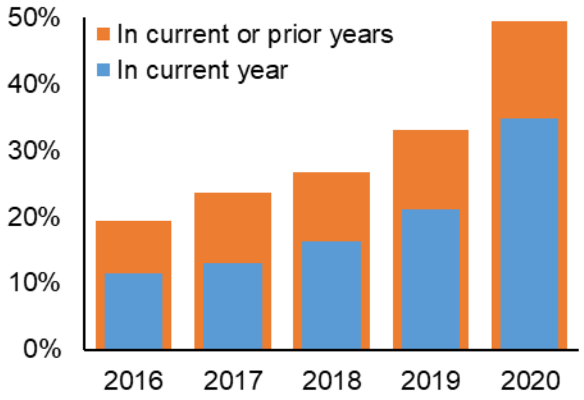
Installer Market Characteristics

Residential Solar+Storage Installer Activity

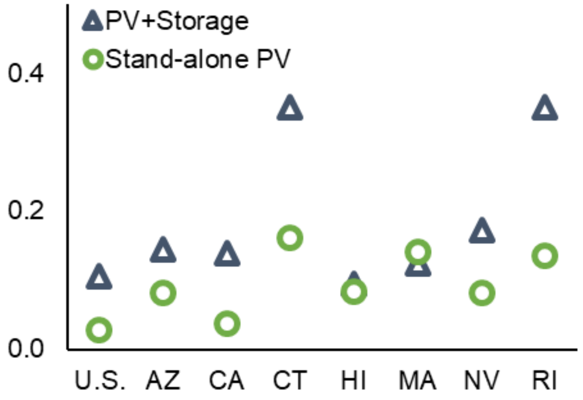
Focusing on installs in 2020

% of Residential PV Installers with at Least 1 PV+Storage Install



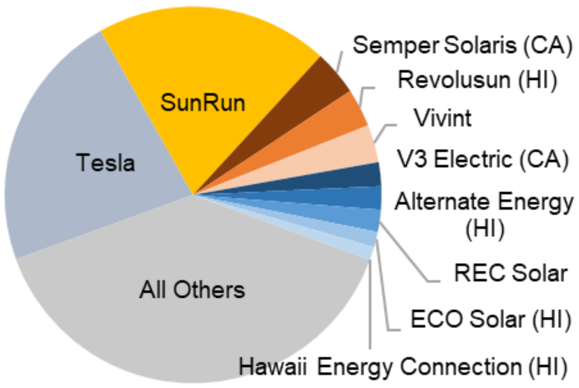
Market Concentration Level (HHI)*

Based on 2020 residential installs



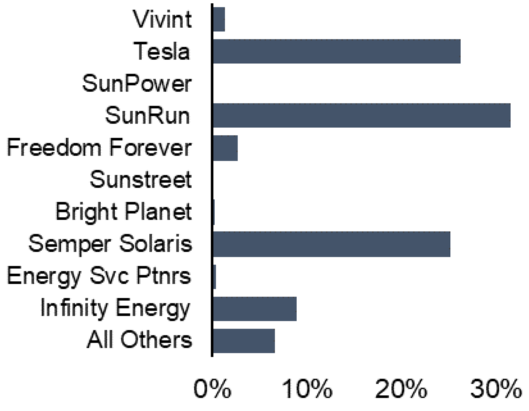
Market Shares

U.S. residential PV+storage installs in 2020



Installer-Level Attachment Rates

California (2020): top-10 installers & all others



- Installer activity has grown over time, with 50% of all active residential installers in 2020 having completed at least one PV+storage system
- The market for PV+storage is considerably more concentrated than for stand-alone PV, as indicated by HHI* values
- Ten firms comprised about 60% of all U.S. residential PV+storage installs in 2020: Tesla and SunRun each had ~20% share; most others in the top-10 are local HI & CA firms
- Installer-level attachment rates in CA are quite bifurcated, even among the largest installers, suggesting divergent business and marketing strategies

**The Herfindahl-Hirschman Index (HHI) is calculated as the sum of the square of each installer's market share. We calculate HHI based on national and statewide market shares, but when used to formally evaluate market competitiveness, more-precise geographical definitions are required.*

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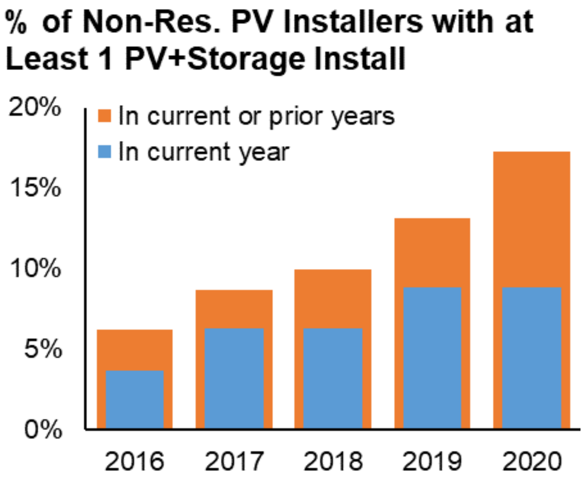
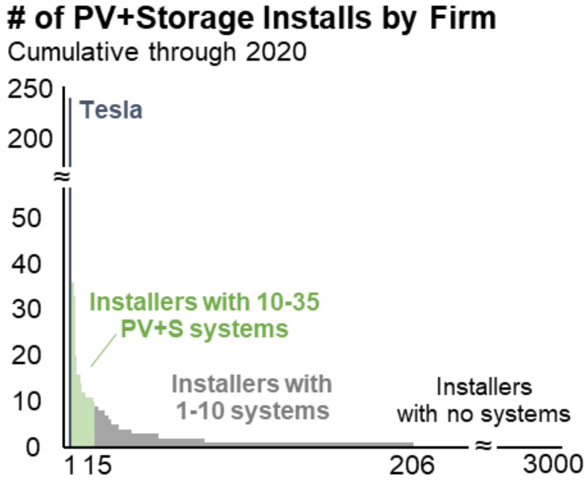
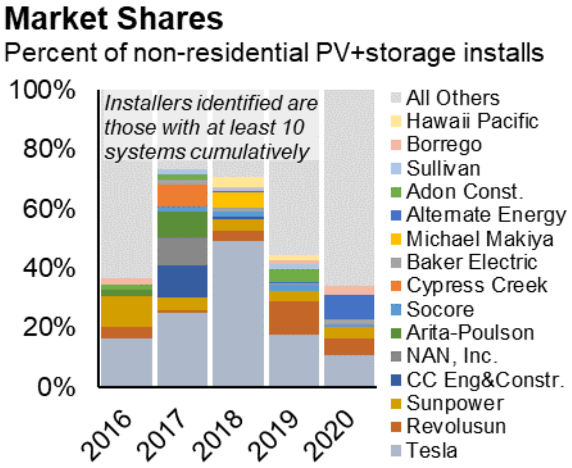
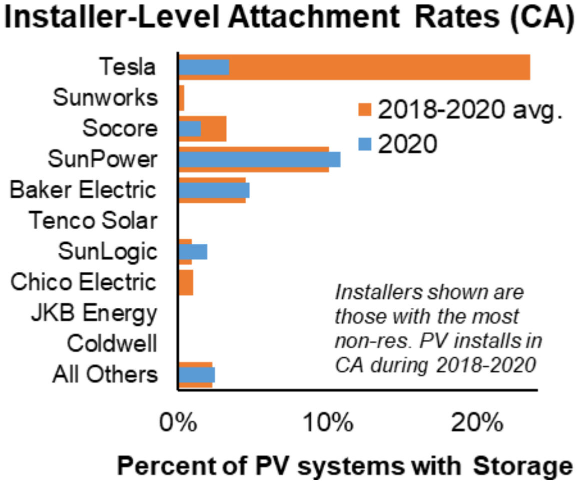
Non-Residential Solar+Storage Installer Activity

Focusing on cumulative installs through 2020









- Storage uptake among non-res. PV installers remains fairly specialized, with just 17% of firms having completed at least 1 PV+storage system *through* 2020, and 8% *in* 2020
- The depth of experience is uneven: among firms with solar+storage installs, Tesla stands out with >200 cumulatively; 14 other firms have 10-35, but most have just 1 or 2
- The non-res. PV+storage installer market has diversified over the past few years, with Tesla's share receding to 10% in 2020 and 66% of all installs by firms with few (<10) prior systems
- Among large non-res. PV installers in CA, attachment rates in 2020 ranged from 0-11% (the highest being SunPower), though Tesla had had much higher rates in recent years

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Installed Pricing: *Estimating the "Premium" for Adding Storage to PV*

Three (Complementary) Data Sources

Tracking the Sun

- Reported total installed price for paired PV+storage and stand-alone PV systems
- Denominated in terms of $/W of PV capacity **($/W$_{PV}$)**
- Installed-price comparisons limited to host-owned systems
- Pricing data for paired PV+storage systems are ***almost entirely from CA***
- Regression analysis to estimate the installed price premium for adding storage

CA SGIP

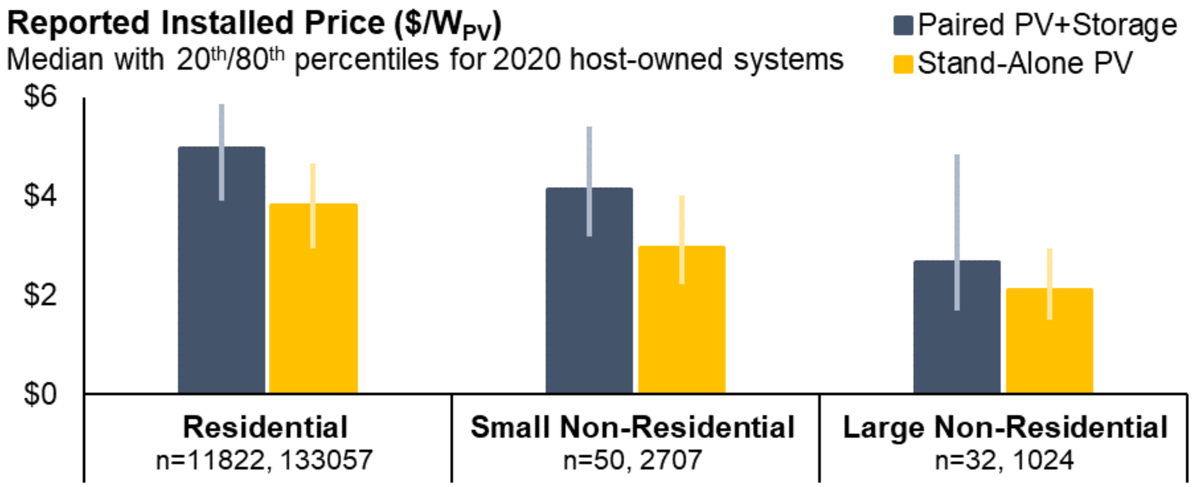
- Reported “eligible costs” for storage systems (most co-installed with PV)
- Denominated in terms of **$/kWh** of storage capacity
- Should *roughly* correspond to the incremental cost of adding storage to PV
- Limited to California
- Includes both host-owned and TPO systems (no ready means to identify TPO)

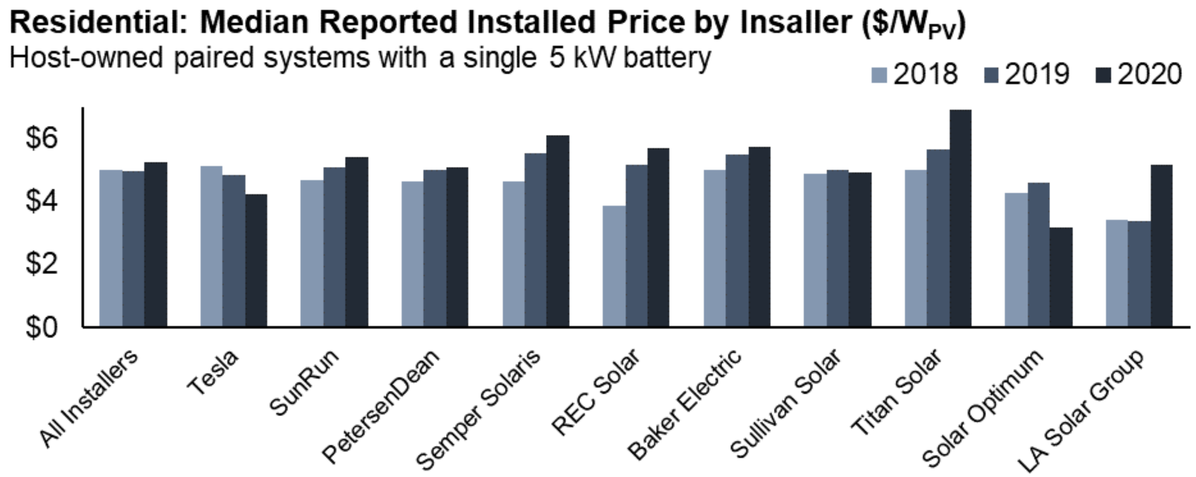
Energy Sage

- Price quotes for paired systems provided both with and without storage
- Allows for direct observation of the storage premium
- Data available for quotes issued since August 2020
- Quotes available for both residential and non-residential systems
- Denominated in terms of both **$/W$_{PV}$** and **$/kWh$_{storage}$**

Reported Installed Prices for PV+Storage Systems

Based on the Tracking the Sun dataset; primarily reflects CA





- Installed prices for paired PV systems vary widely, even more than for stand-alone, indicative of a less-mature market
- The median installed price of paired residential systems was $5.0/W$_{PV}$ in 2019, roughly **$1.2/W$_{PV}$ (33%)** higher than stand-alone PV
  - Equates to storage cost of ~$700/kWh, assuming typical PV and storage sizes
- Installed prices for non-residential paired systems are also generally higher than for stand-alone PV, but sample sizes are small
- Installed prices reported for paired residential systems have *risen* in recent years across most installers (Tesla being one exception)
  - Potentially reflecting supply-chain constraints and value-based pricing

Notes: In the top figure, "Small" vs. "Large" Non-Residential is based on a 100 kW-PV size threshold. The 10 installers shown in the bottom figure are those with the most data points over the 2018-2020 period.

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Statistical Estimate of the Storage "Price Premium" for Residential PV

We apply a multi-variate regression analysis to estimate the effect of adding storage on the overall installed price of residential PV+storage systems, based on Tracking the Sun data

- Based on a variation of the statistical model employed in Berkeley Lab's Tracking the Sun: 2019 Edition, used to explain overall variation in residential PV installed prices

$$p = \alpha + system\beta_1 + market\beta_2 + installer\beta_3 + S + Q + I + \varepsilon_i$$

- Dependent variable (*p*) is installed price (in $/W); independent variables include system, market, and installer-level factors, as well as state (*S*), quarterly (*Q*), and installer (*I*) fixed-effects variables
- To estimate the installed-price premium for adding storage, we include a binary variable (among the vector of system-level variables) to indicate whether the system includes storage

Results: Across several different model specifications and sample frames, we estimate an average installed-price premium of **$1.15-1.46/W$_{PV}$** for adding storage to host-owned residential PV systems in 2019, though some installers exhibit smaller or larger premiums

See appendix for further details on model specification and results

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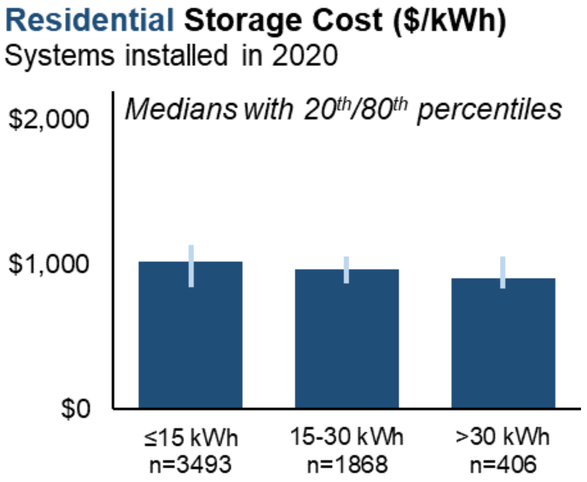
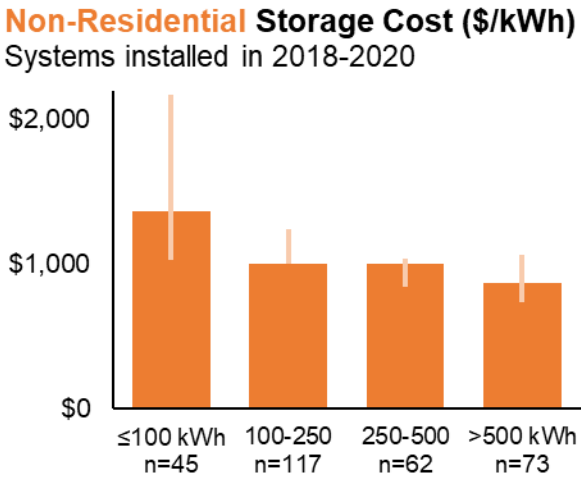
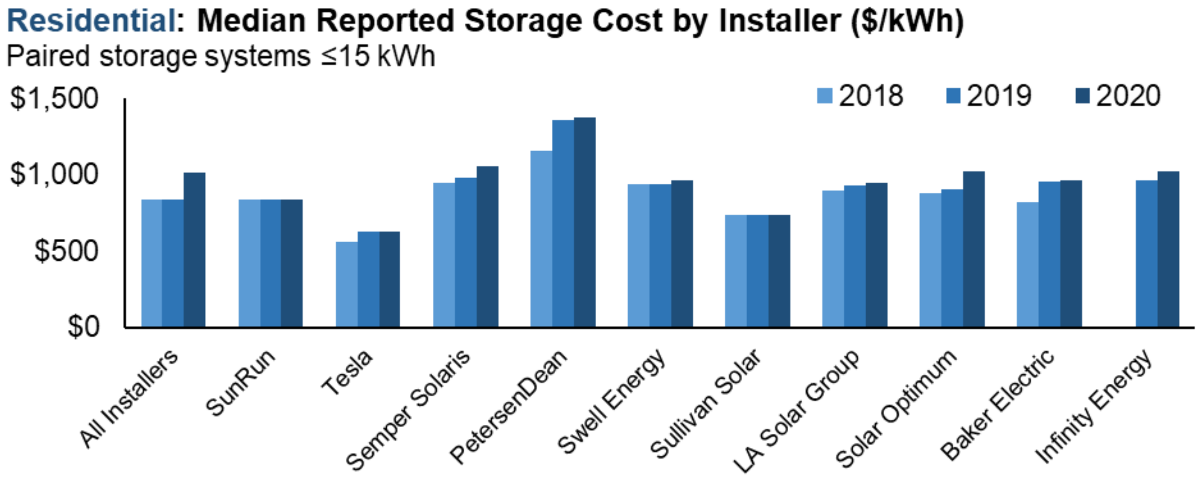
CA SGIP Reported Eligible Costs

For storage systems paired with PV





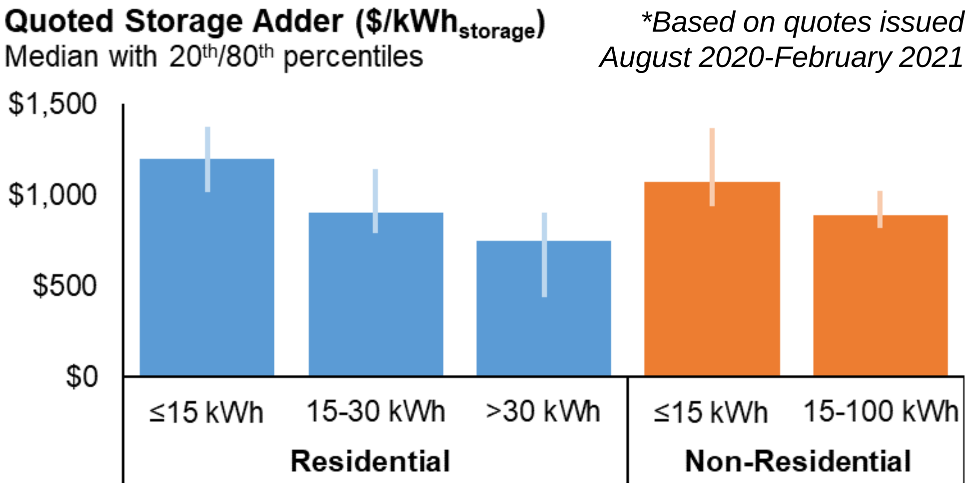


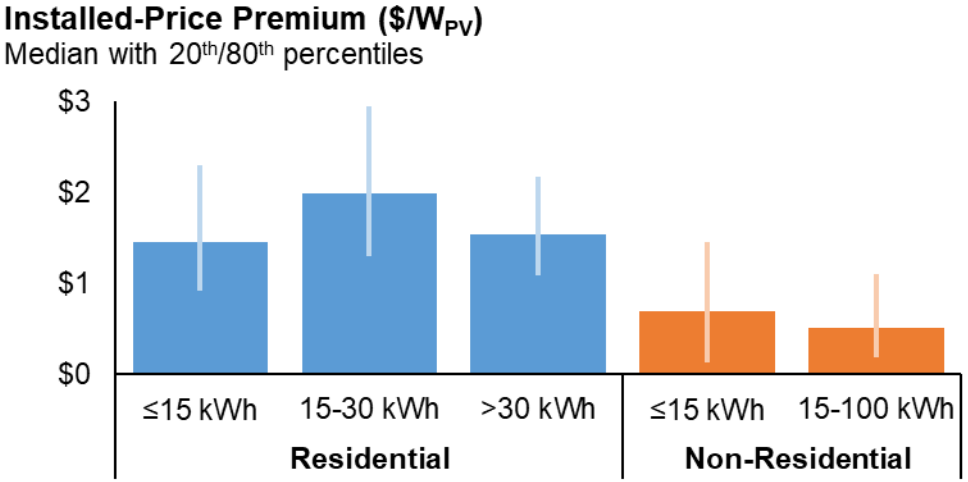
- Median reported storage costs of roughly **$1,000/kWh** for residential systems
- Costs for non-residential systems vary widely, and generally decline on a per-kWh basis with larger sizes, but center around $1,000/kWh for systems in the 100-500 kWh size range
- Reported storage costs for residential systems have generally risen over time across most of the larger installers, consistent with the system-level installed pricing data collected through Tracking the Sun
- The SGIP data do exhibit some notable "quirks" among individual installers: e.g., all SunRun systems are reported at exactly $834/kWh; Tesla-reported prices are low and may exclude installation costs

Notes: Values shown for non-residential systems are based on systems installed over 2018-2020, due to small sample sizes. The 10 installers shown in the bottom figure are those with the most data points over the 2018-2020 period.

Energy Sage Price Quotes

Storage Adder and Installed-Price Premium





- Many installer price quotes on EnergySage provide an explicit adder for including storage with the quoted PV system
- Median storage adder was **$1200/kWh** for residential systems <15 kWh, and slightly less for similarly sized non-residential systems, with clear economies of scale (top figure)
- Equates to a median **$1.5/W$_{PV}$** installed-price premium for residential systems with <15 kWh storage (bottom figure)
- Installed-price premiums for larger storage system sizes and for non-residential PV systems also provided for reference, but their interpretation is less straightforward without correlating in some way to PV system sizes

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Synthesis of Installed Pricing and Cost Data (Residential)

A few other relevant data points:

- Tesla provides online quotes for both stand-alone PV and paired PV+storage systems: the quoted cost of adding storage to PV is currently $10,500 for a single PowerWall, inclusive of gateway and installation costs, equating to **~$800/kWh**
- NREL's U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020 report estimates a cost of roughly **$1300/kWh** to add 6 kWh storage to residential PV, which equates to an installed price premium of **$1.15/W$_{PV}$**
- Wood MacKenzie's U.S. Energy Storage Monitor Report indicates a median price of $2,700/kW for residential storage in 2020 (not specific to paired storage); equates to **$1,000/kWh** assuming Powerwall duration

Bringing it all together…

Incremental Cost of Adding Storage to PV

~$1,000/kWh$_{storage}$

($700-1,300/kWh across sources; wider spread across individual projects)

Installed-Price Premium for Residential PV

~$1.2/W$_{PV}$

($1.15-1.5/W$_{PV}$ across sources; wider spread across individual projects)

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Does the customer-economics of adding storage to BTM solar currently pencil out?

Basic Approach

- Estimate the financial value (to the host customer) of adding storage to BTM solar in several key markets with relatively high attachment rates
  - Residential: Hawaii (HECO), California (PG&E and SCE), and Arizona (SRP)
  - Non-residential: California (PG&E and SCE)
- Focus on primary financial benefit streams, circa 2020
  - Utility bill savings (incremental to stand-alone PV)
  - State/utility rebates or other direct incentives for BTM storage
  - Federal investment tax credit (ITC)
  - Accelerated depreciation (MACRS)
- Analysis is indicative and retrospective
  - Just a subset of states, focusing on value streams currently and commonly captured by BTM solar+storage
  - Going forward, other emerging value streams, as well as changes to net metering rules and retail electricity rates, will no doubt alter the customer economics in significant ways

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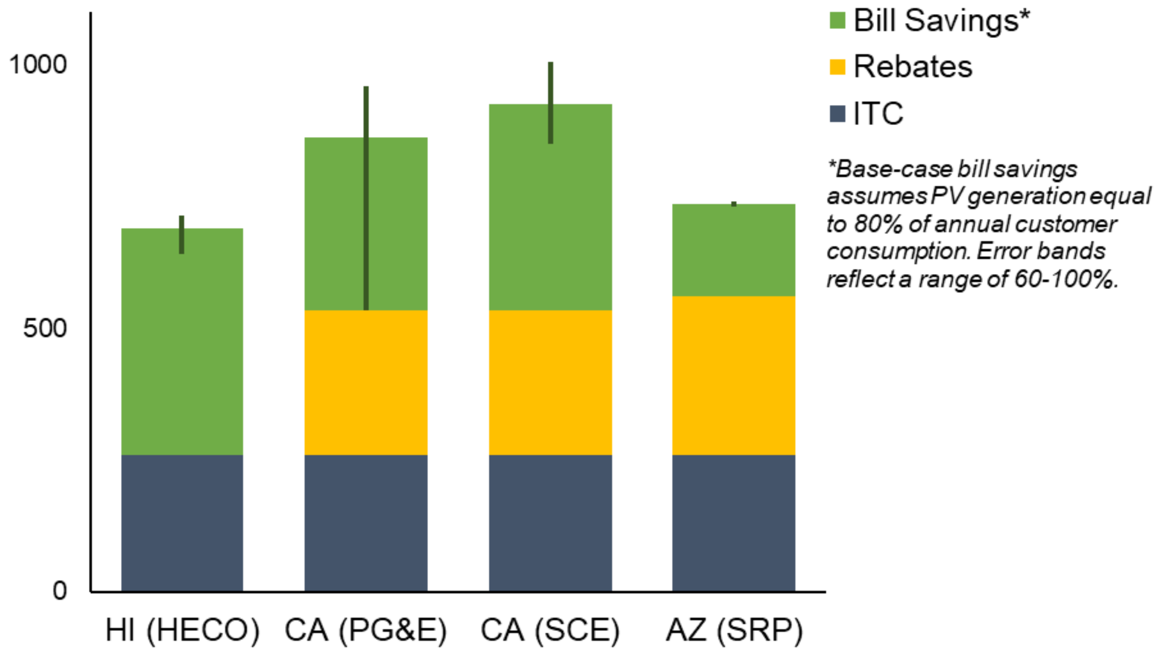
Customer Financial Value of Adding Storage to PV
Indicative *residential* cases

Residential Customer Financial Value of Adding Storage to PV
$/kWh *(calculated on a 10-year present value basis)*



Notes: PV systems sized to meet varying percentages of annual consumption. Storage system sized at 5 kW / 10 kWh. Bill savings calculated using NREL's ReOpt Lite model, comparing annual bills for PV-only and PV+storage configurations, in each case based on the least-cost tariff option available. Annual bill savings discounted assuming a 2.7% real, after-tax weighted average cost of capital. For more information, see "Further Details on Customer-Economics Modeling" in the appendix.

- Bill savings are primarily from arbitraging between export credit rates and retail rates (HI), TOU arbitrage (CA), and demand charge savings (AZ)
- Additional utility rebates are available in CA and AZ, plus federal tax credits
- Total customer financial value of adding storage to PV ranges from roughly $500-1000/kWh across the utilities and PV sizing scenarios shown (low band for PG&E reflects binding minimum bills for customers with relatively large PV systems)
- Given the cost of adding storage to PV ($700-1200/kWh), the economics appear borderline in these markets, at least based on these cases
  - In CA, storage makes the most sense for customers with relatively small PV systems and/or large loads
- Suggests that co-adoption likely driven to a significant degree by non-financial considerations (e.g., resilience value)

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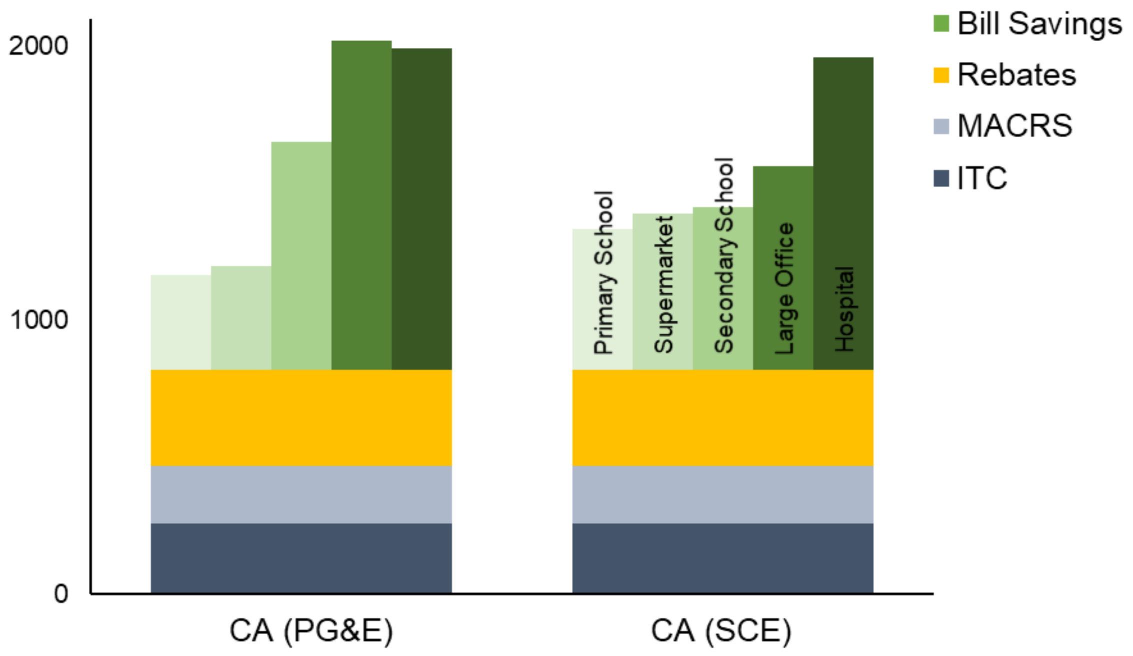
Customer Financial Value of Adding Storage to PV

Indicative *non-residential* cases

Non-Res. Customer Financial Value of Adding Storage to PV
$/kWh *(calculated on a 10-year present value basis)*



Notes: Assumes a 200 kW PV system with a 100 kW / 200 kWh battery. ITC based on 26% tax credit rate and $1000/kWh installed cost of storage. MACRS benefit equivalent to 21% of installed cost (NREL 2018). Bill savings calculated using NREL's ReOpt Lite model, comparing annual bills for PV-only and PV+storage configurations, in each case based on the least-cost tariff option available for customers of the assumed size. Annual bill savings discounted assuming a 3.5% real, after-tax weighted average cost of capital. For more information, see "Further Details on Customer-Economics Modeling" in the appendix.

- Customer-value of adding storage to PV ranges from $1200-2000/kWh across the modeled non-residential building types (selected on the basis of being large enough to host a 200 kW PV system)
- Generally much higher value than what we find on the residential side, owing to:
  1. Additional tax incentive available through accelerated depreciation (MACRS)
  2. Rate structures for medium/large C&I customers with relatively high demand charges ($13-25/kW, across the rate options considered here)
- But yet pairing with storage is much less common for non-residential PV than for residential PV:
  - Pool of non-residential PV adopters on high demand-charge rates may be limited
  - Non-residential customers have different motivations, and perhaps more stringent financial criteria than residential PV adopters

What level of backup power protection can residential solar+storage offer?

(as currently deployed)

Basic Approach

Using simulated data, estimate the percentage of a residential customer's consumption, each day, that could be served by BTM PV+storage

Provides a rough sense for how much load could be maintained during an extended outage; more complex approaches are certainly possible (e.g., stochastic outages, multi-day outages, consideration of EE and DR, etc.)

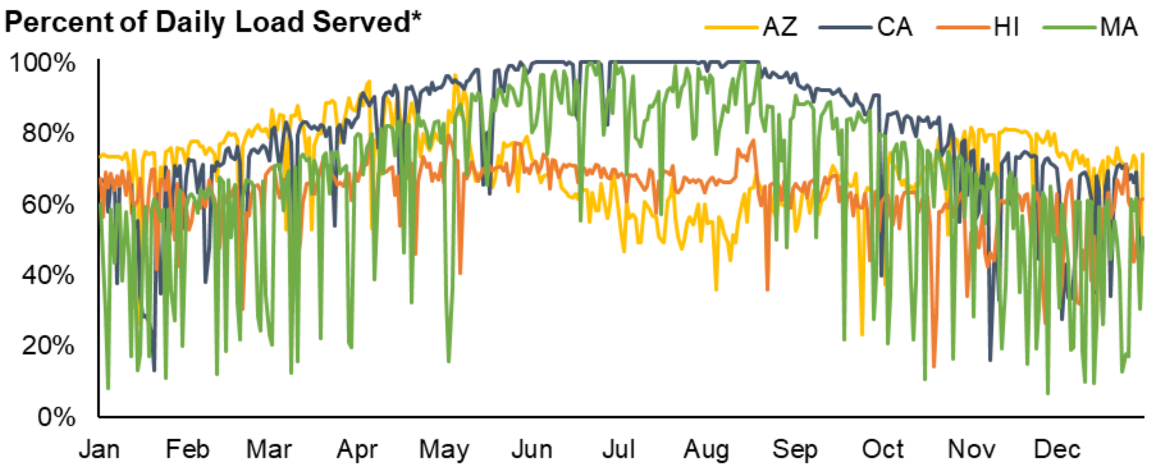
- Focus on four states (AZ, CA, HI, MA) with relatively high uptake and diverse climates, considering both average- and high-consumption residential customers
- Assume a standard configuration (7 kW PV with 5 kW/10 kWh storage)
- Separate from the above, estimate the system size required to meet increasing percentages of annual customer load, all the way up to full "grid defection"

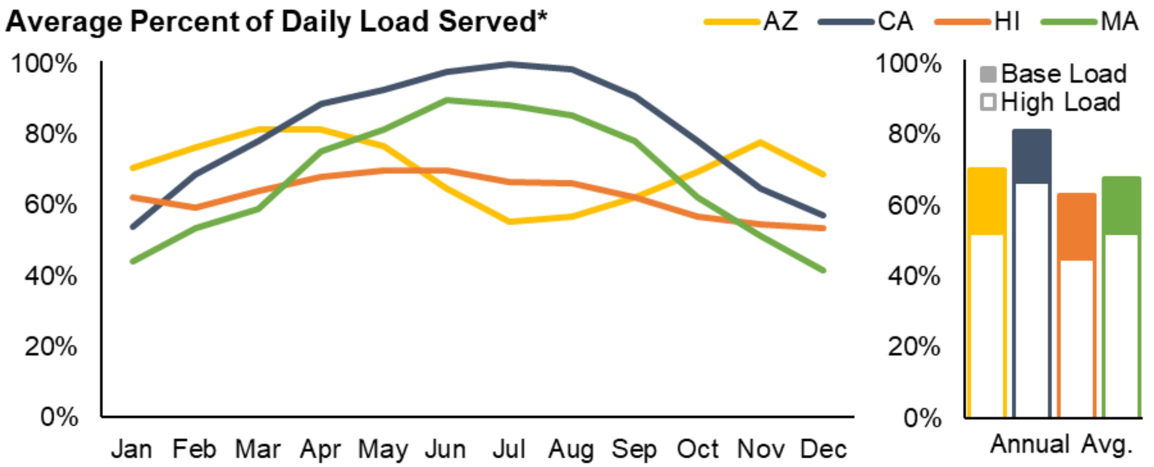
See appendix for further details on the methods and data sources

Percent of Daily Load That Could Be Served

By a Typical PV+Storage System Configuration

- Can vary widely on a day-to-day basis, as a function of weather; regions with more frequent cloudiness (e.g., MA) see more variability
- Generally higher in summer months, due to greater solar generation
  - But can be lower in summer months in regions (AZ) with especially high cooling loads
- Annual averages range from 60% (HI) to 80% (CA) of daily load served, for residential customers with average levels in each state
  - Cross-state differences reflect varying absolute consumption levels (HI >> CA)
  - Percentages are lower (45-65%) for high-consumption customers

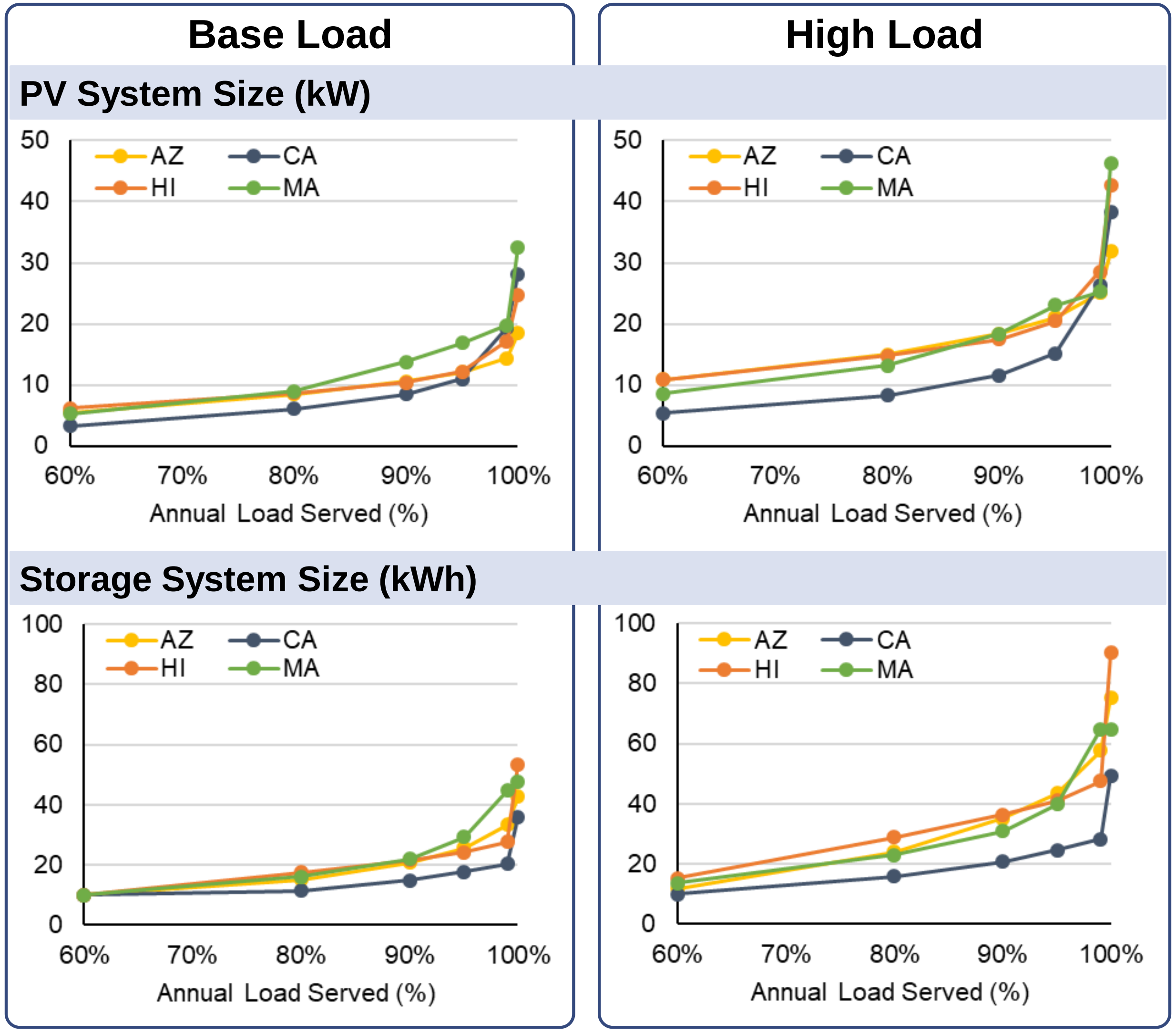




* *Daily and monthly values are shown for customers with average consumption levels in each state ("Base Load"); the chart with annual averages also shows results for customers with high consumption levels ("High Load"). See appendix for further details.*

How large would the system need to be to maintain higher levels of load served?

- Meeting 90% of annual load* would require 8-14 kW PV & 15-22 kWh storage, depending on the state, for customers with avg. consumption
  - Larger than typical system sizes, but not dramatically so
- Required system sizes increase significantly to maintain higher levels of annual load served (with a sharp kink from 99% to 100% of load)
- System sizes would need to be considerably larger for high-consumption customers
- Energy efficiency and load flexibility—not considered here—could enable smaller solar+storage system sizing



* *The metric used here is the percentage of total annual load served, and thus the actual percentage of load served on any given day could be higher or lower than this amount. To maintain some minimum percentage of load served on each day would require larger system sizes.*

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Conclusions

Conclusions

- BTM solar+storage is growing, at least within the residential sector, but is still a small part of the broader solar market
- The supply-side of the market is fairly concentrated in terms of both manufacturers and installers, though a significant share of PV installers has entered the solar+storage space, at least to some limited extent
- Installed prices for BTM battery systems have generally risen or remained flat over the past few years; increasing adoption can’t be attributed to falling retail costs
- Deployment drivers are locationally specific (e.g., specific rate structures, incentive programs, natural disaster threats)
- Deployment trends partly reflect the underlying economics, but there are also some *apparent* disconnects (e.g., lower attachment rates for non-residential than residential, divergent attachment rates across regions with similar payback, un-economic adoption in some markets)
- Those apparent disconnects may partly reflect other sources of value beyond the direct financial benefits—including potential customer reliability benefits from backup power during outages

Appendix

Details on Data Sources and State Sample Sizes

State	Data Sources	Scope of Coverage / Limitations	Residential Sample (# of Paired Systems)							Non-Residential Sample (# of Paired Systems)						
			<2016	2016	2017	2018	2019	2020	*Total*	<2016	2016	2017	2018	2019	2020	*Total*
AZ	APS, SRP, TEP	All interconnected systems in utility service territory	90	41	93	718	581	894	*2,417*	0	1	3	0	5	9	*18*
CA	IOUs, LADWP, SMUD	All interconnected systems in utility service territory	372	162	1,064	7,065	9,939	15,911	*34,513*	58	48	68	189	132	103	*598*
CO	Xcel	All interconnected systems in utility service territory	0	0	7	192	202	118	*519*	0	0	0	1	2	5	*8*
CT	CGB	All funded systems	1	3	2	70	94	188	*358*	0	0	0	0	0	0	*0*
FL	GRU, OUC	All funded systems	0	2	0	24	49	63	*138*	0	0	0	0	0	1	*1*
HI	Ohm Analytics	All permits issued on Oahu	0	1	615	1,621	2,785	3,112	*8,134*	0	0	6	24	45	43	*118*
IL	IPA	Adjustable Block program	0	0	0	14	63	39	*116*	0	0	0	0	2	2	*4*
MA	MA DOER	SMART program	0	0	0	40	257	391	*688*	0	0	0	3	17	20	*40*
MN	Xcel	All interconnected systems in utility service territory	5	0	3	16	14	26	*64*	0	0	0	0	0	0	*0*
NC	NCSEA	Partial identification of systems receiving CPCN	1	0	1	1	8	170	*181*	1	0	12	0	1	0	*14*
NJ	NJ BPU	Partial identification of funded systems	0	0	39	130	186	131	*486*	0	2	1	0	2	0	*5*
NM	NM EMNRD	Partial identification of funded systems	0	0	0	0	0	31	*31*	0	0	0	0	0	1	*1*
NV	NV Energy	All interconnected systems in utility service territory	0	0	15	131	246	337	*729*	0	0	0	1	0	2	*3*
NY	NYSERDA	Partial identification of funded systems	0	0	0	0	22	253	*275*	0	0	0	0	1	1	*2*
OR	Energy Trust of Oregon	All funded systems	35	24	89	58	35	63	*304*	5	0	4	4	2	6	*21*
PA	DEP	All funded systems (via legacy rebate program)	26	0	0	0	0	0	*26*	1	0	0	0	0	0	*1*
RI	National Grid, RICC	All interconnected systems in utility service territory	2	0	0	21	42	63	*128*	0	0	0	1	1	2	*4*
TX	Austin Energy, CPS	All funded systems	2	3	14	29	28	18	*94*	3	0	0	0	0	0	*3*
UT	OED	All funded systems	12	27	91	94	217	12	*453*	0	0	1	4	10	1	*16*
WA	PSE	All interconnected systems in utility service territory	126	36	27	41	87	142	*459*	8	1	0	1	1	1	*12*
		Total	**672**	**299**	**2,060**	**10,265**	**14,855**	**21,962**	***50,113***	**76**	**52**	**95**	**228**	**221**	**197**	***869***

Installed-Price Regression Variables (Base Model)

System-Level Variables	
kW	System capacity in kW
kW^2	Squared term of system capacity
Battery	Dummy variable indicating whether system has a battery
Premium modules	Dummy variable indicating whether system uses a premium-efficiency module
Microinverter	Dummy variable indicating whether system uses a microinverter
DC optimizer	Dummy variable indicating whether system uses a DC optimizer
Ground-mounting	Dummy variable indicating a ground-mounted PV system
New construction	Dummy variable indicating if system was installed during new construction
Market-Level Variables	
HHI	The Herfindahl-Hirschman Index (HHI), which measures the level of market concentration among installers
HHI^2	Squared term of HHI
Market size	Number of systems installed in the customer's market in 2019
Household density	Number of households per square mile in customer's market
Median income	Median household income in customer's zip code
Installer-Level Variables	
Installer experience	Cumulative number of systems installed by the installer, depreciated at 20% per quarter
Fixed Effects Variables	
Installer	Fixed effects variable for the 10 installers with the most paired residential PV systems in 2019
State	Fixed effects variable for each state
Quarter	Fixed effects for each quarter

Installed-Price Regression Results: Models 1-4

- The table shows the results from four different model or sample specifications:
  (1) Base model with coefficients estimated for all host-owned residential systems installed in 2019
  (2) Same as (1) but sample is limited to installers with at least one paired system
  (3) Same as (1) but dropping Sunrun and Tesla from the sample
  (4) Same as (1) but without the installer fixed effects (FE) variables
- Coefficients for battery variable (representing the impact of storage on total system installed price in $/W-pv) range from 1.15 to 1.46, and are all statistically significant

Variable	Model/Sample Specification			
	(1)	(2)	(3)	(4)
Battery	**1.29* (0.02)**	**1.26* (0.02)**	**1.46* (0.02)**	**1.15* (0.02)**
kW	-0.31* (0.01)	-0.3* (0.01)	-0.32* (0.01)	-0.31* (0.01)
kW^2	0.01* (0)	0.01* (0)	0.01* (0)	0.01* (0)
Premium module	-0.07* (0.01)	-0.06* (0.01)	-0.09* (0.01)	-0.04* (0.01)
Microinverter	0.13* (0.02)	-0.06* (0.02)	0.34* (0.02)	0.26* (0.02)
DC optimizer	0.17* (0.02)	0.09* (0.02)	0.36* (0.02)	0.28* (0.01)
HHI	-0.63* (0.17)	-0.66* (0.22)	-0.82* (0.19)	-0.98* (0.17)
HHI^2	0.05 (0.26)	0.17 (0.37)	0.37 (0.28)	0.43 (0.26)
Market size (x1000)	-0.03* (0)	-0.02* (0)	-0.03* (0)	-0.03* (0)
Inst. experience (x1000)	0.01* (0)	0.01* (0)	0.01* (0)	0* (0)
HH/sq. mi (x1000)	0.07* (0)	0.05* (0)	0.08* (0)	0.06* (0)
Median income (x1000)	0* (0)	0* (0)	0* (0)	0* (0)
New construction	-0.23* (0.03)	-0.63* (0.17)	-0.26* (0.03)	-0.19* (0.03)
Groundmount	0.23* (0.03)	0.41* (0.04)	0.26* (0.03)	0.27* (0.03)
State FE	X	X	X	X
Quarter	X	X	X	X
Installer FE	X	X	X	
N	99,183	59,685	87,548	99,183

Installed-Price Regression Results: Model 5

- A fifth model specification was used to estimate installer-specific storage premiums
- To do this, the model includes two FE variables for each of the top-ten PV+storage installers in 2019: one FE variable for its stand-alone PV systems and one for its paired systems (in lieu of the battery variable in the base model)
- The *difference* between each installer's coefficients for paired and stand-alone PV can be interpreted as its price premium for systems with storage
- Based on this approach, **most installers' storage premiums range from $1.25-1.86/W**, though several fall well outside that range (most notably Tesla, with a derived premium of $0.71/W)

Installer	Coefficient (stand-alone PV)	Coefficient (paired PV+storage)	Derived Premium for Storage
Baker Electric	0.18* (0.03)	2.23* (0.1)	2.05
Hot Purple Energy	-0.33* (0.11)	-0.72* (0.13)	-0.39
Petersen Dean	-0.61* (0.03)	1.25* (0.06)	1.86
Rec Solar	-0.1* (0.04)	1.36* (0.06)	1.46
Semper Solaris Construction	-0.33* (0.02)	1.49* (0.07)	1.82
Solar Optimum	-0.71* (0.06)	0.87* (0.13)	1.58
Sullivan Solar Power	0.07 (0.04)	1.35* (0.13)	1.28
Sunrun	-0.35* (0.02)	1.17* (0.03)	1.52
Tesla Energy	-0.25* (0.03)	0.46* (0.04)	0.71
Titan Solar Power	0.32* (0.03)	1.79* (0.13)	1.42
Other Installer	n/a	1.25* (0.03)	1.25

Further Details on Customer-Economics Modeling

Estimating incremental bill savings from adding storage to PV

- Hourly load profiles based on simulated customer loads accessed through NREL's OpenEI data portal, for the 2016 weather year and for base-consumption customers in each of the analysis locations: Honolulu (HECO), San Francisco (PG&E), Los Angeles (SCE), and Phoenix (SRP)
- NREL's ReOpt Lite used to simulate storage dispatch and calculate utility bills for PV-only and PV+storage
- Post-processing of ReOpt outputs required in order to: (a) impose minimum bill requirements for CA utilities and (b) manually calculate export credits under net billing rates for SRP's E-13 rate and HECO's Customer Grid Supply Plus tariff option
- For both PV-only and PV+storage, utility bills estimated across all available tariff options for each utility and PV size; incremental savings from storage estimated assuming least-cost tariff for each scenario

Other key assumptions

- ITC based on 26% tax credit rate and $1000/kWh installed cost of storage.
- Rebates in CA based on standard SGIP incentive rates offered in 2020 for residential and non-residential storage (incentives for "equity" and "equity-resilience" applications were considerably higher)
- ITC and MACRS calculated assuming storage cost of $1000/kWh, with a 26% ITC and MACRS benefit equal to 21% of the installed cost, based on 5-year accelerated depreciation (see NREL 2018)

Further Details on Customer-Reliability Modeling

Two separate analyses performed

1. Estimate the percentage of daily customer load that could be met by solar+storage, given typical system sizes (7 kW PV with a 5 kW/10 kWh storage system)*
2. Estimate how large solar+storage systems would need to be in order to maintain specified percentages of annual customer load

Common elements

- Hourly load profiles based on simulated customer loads accessed through NREL's OpenEI data portal, based TMY weather files and for base- and high-consumption customers in each of the analysis locations
- PV simulated using NREL's SAM model, based on the same locations and TMY weather
- Storage dispatched solely for meeting customer load demands, rather than for customer bill minimization
- Analysis performed using julia scripts developed in Gorman et al. 2020

* For reference, "critical" loads, such as refrigerators, lights, and computer technologies typically represent ~20% of customer energy needs, depending on home location and appliance usage, though percentage will vary widely for individual households. For more, see https://www.eia.gov/tools/faqs/faq.php?id=96&t=3

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