Identifying Critical Factors in the Cost-effectiveness of Solar and Battery Storage in Commercial Buildings

Joyce McLaren (joyce.mclaren@nrel.gov)
Kate Anderson, Nick Laws, Pieter Gagnon, Nicholas DiOrio, Xiangkun Li

February 2018

NREL/PR-6A20-70813

Contents

Identifying Critical Factors in the Cost-effectiveness of Solar and Battery Storage in Commercial Buildings

This analysis elucidates the emerging market for distributed solar paired with battery energy storage in commercial buildings across the United States. It provides insight into the near-term and future solar and solar-plus-storage market opportunities as well as the variables that impact the expected savings from installing behind-the-meter systems.

This work is the result of a two-year research project conducted at the National Renewable Energy Laboratory funded by the U.S. Department of Energy's Solar Energy Technologies Office. Please see the project website at https://openei.org/wiki/Solar+Storage.

Questions Addressed

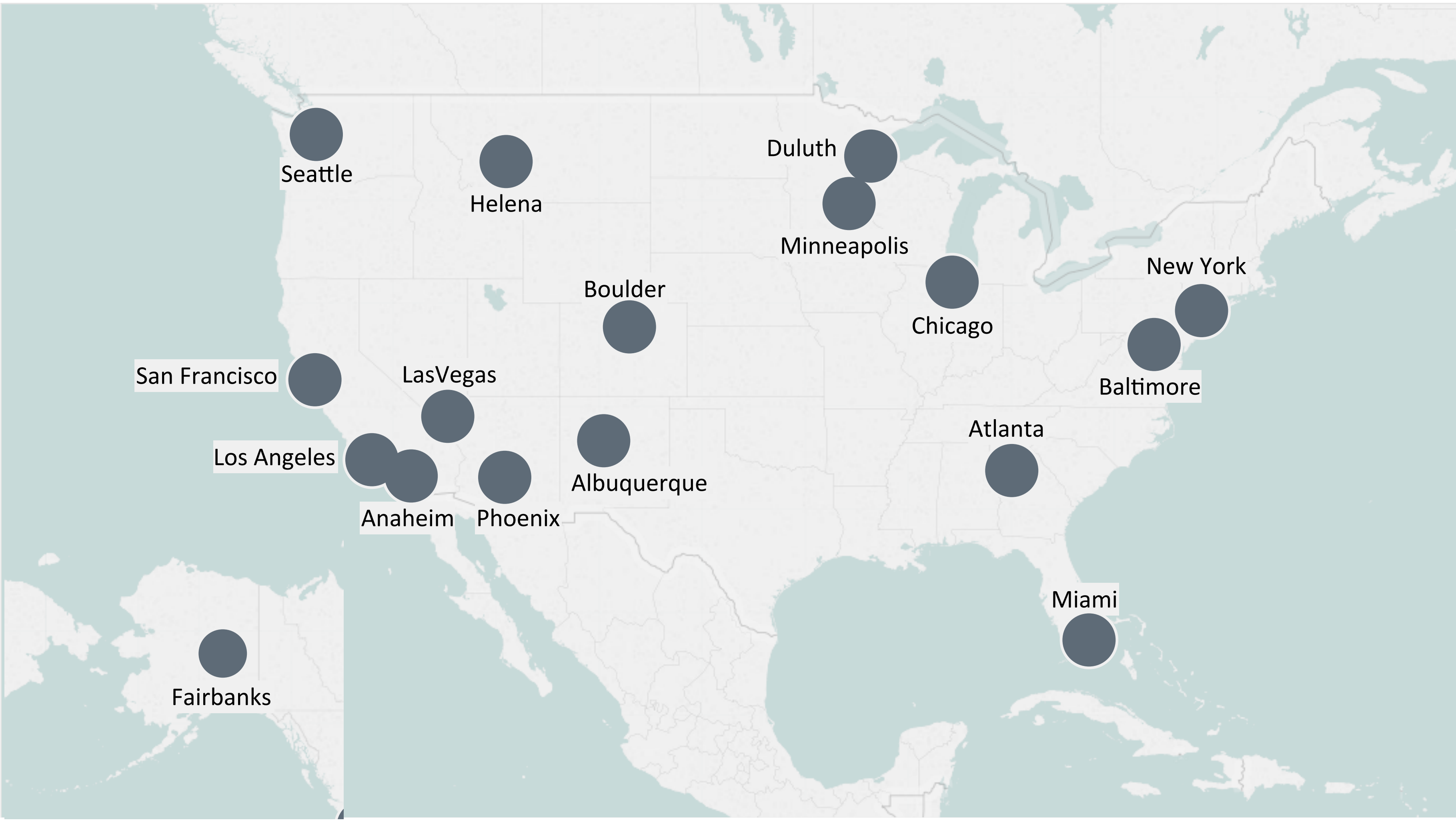
Solar + Storage

Questions answered by this research include:

- Are solar and/or storage economical in my location?
- Which commercial building types are most likely to see cost-savings from solar and/or storage?
- Where are the emerging markets for solar and/or storage?
- Which utility rate structures encourage solar and/or storage deployment?
- How do cost-optimal system sizes vary across buildings and locations?
- What is the role of policies and incentives in solar and/or storage economics?

Locations Modeled

Cost-optimal solar and/or battery storage system configurations were identified for 17 locations, 73 utility rates, 16 commercial building types, and multiple technology cost points.



Scenarios Modeled

More than 24,000 scenarios were modeled to identify cost-optimal solar and/or battery storage system configurations for 73 commercial electricity rates for the utilities with the largest number of customers in each climate zone.

Climate Zone	City	Utility	Number of Rates Modeled	Number of Building Types Modeled	Number of Scenarios Modeled
1A	Miami	Florida Power & Light Co	4	15	1,050
2B	Phoenix	Salt River Project	4	16	1,260
3A	Atlanta	Georgia Power Co	4	16	1,645
3B	Los Angeles	Los Angeles Department of Water & Power	3	16	595
	LasVegas	Nevada Power Co	5	16	1,960
	Anaheim	Southern California Edison Co	10	16	2,099
3C	San Francisco	Pacific Gas & Electric Co	8	16	2,552
4A	New York	Consolidated Edison Co-NY Inc	3	16	1,119
	Baltimore	Baltimore Gas & Electric Co	4	16	1,120
4B	Albuquerque	Public Service Co of NM	4	15	700
4C	Seattle	City of Seattle Washington	8	16	2,310
5A	Chicago	Commonwealth Edison Co	3	16	1,680
5B	Boulder	Public Service Co of Colorado	2	16	980
6A	Minneapolis	Minnesota Power Inc	2	16	1,120
6B	Helena	NorthWestern Corporation	4	16	2,240
7	Duluth	Northern States Power Co - Minnesota	3	16	1,085
8	Fairbanks	Golden Valley Elec Assn Inc	2	16	630
		Grand Total	73	270	24,145

https://openei.org/wiki/Solar+Storage

Commercial Building Types Modeled

Hourly annual load profiles were generated for 16 commercial building types, based on the Department of Energy's Commercial Reference Buildings.

Building Type	Annual Energy Consumption (kWh)	Peak Annual Demand (kW)
Hospital	8,654,762	1,620
Large Office	6,524,278	1,831
Secondary School	2,689,236	1,138
Large Hotel	2,488,769	606
Supermarket	1,979,115	435
Outpatient	1,601,198	370
Primary School	1,079,781	380
Medium Office	925,051	350
Small Hotel	764,771	173
Retail Store	514,380	153
Strip Mall	509,387	152
Restaurant	342,943	71
Midrise Apartment	272,544	82
Warehouse	222,718	75
Fast Food	192,700	38
Small Office	87,369	26

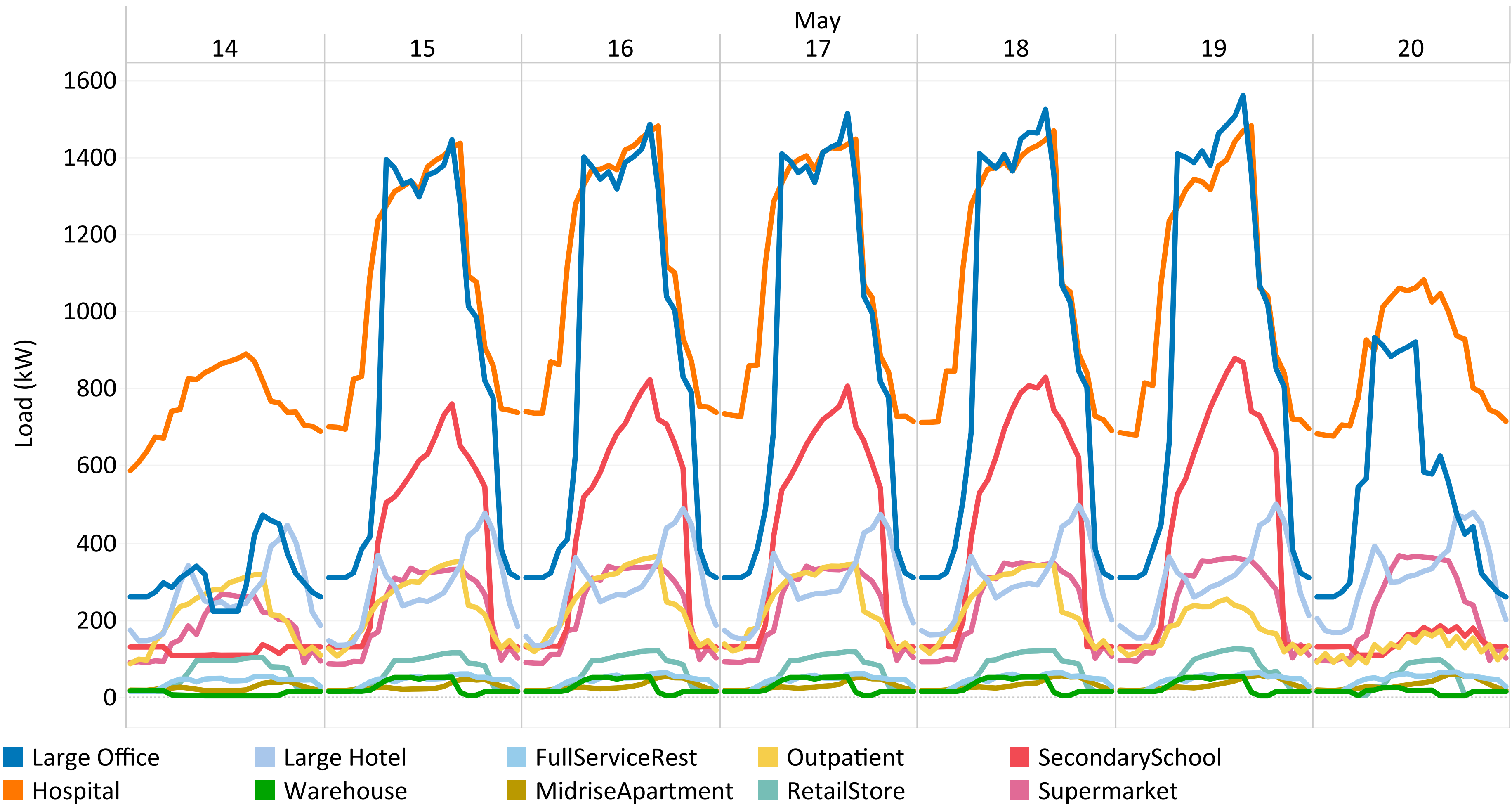
Note: Figures shown here are an average of all locations modeled.

https://openei.org/wiki/Solar+Storage

Commercial Building Loads Modeled

The hourly annual load profiles were adjusted for typical meteorological year (TMY) data. Rates and building types were matched based on the load profile of the building and the eligibility requirements stated in the utility's rate tariff sheet.

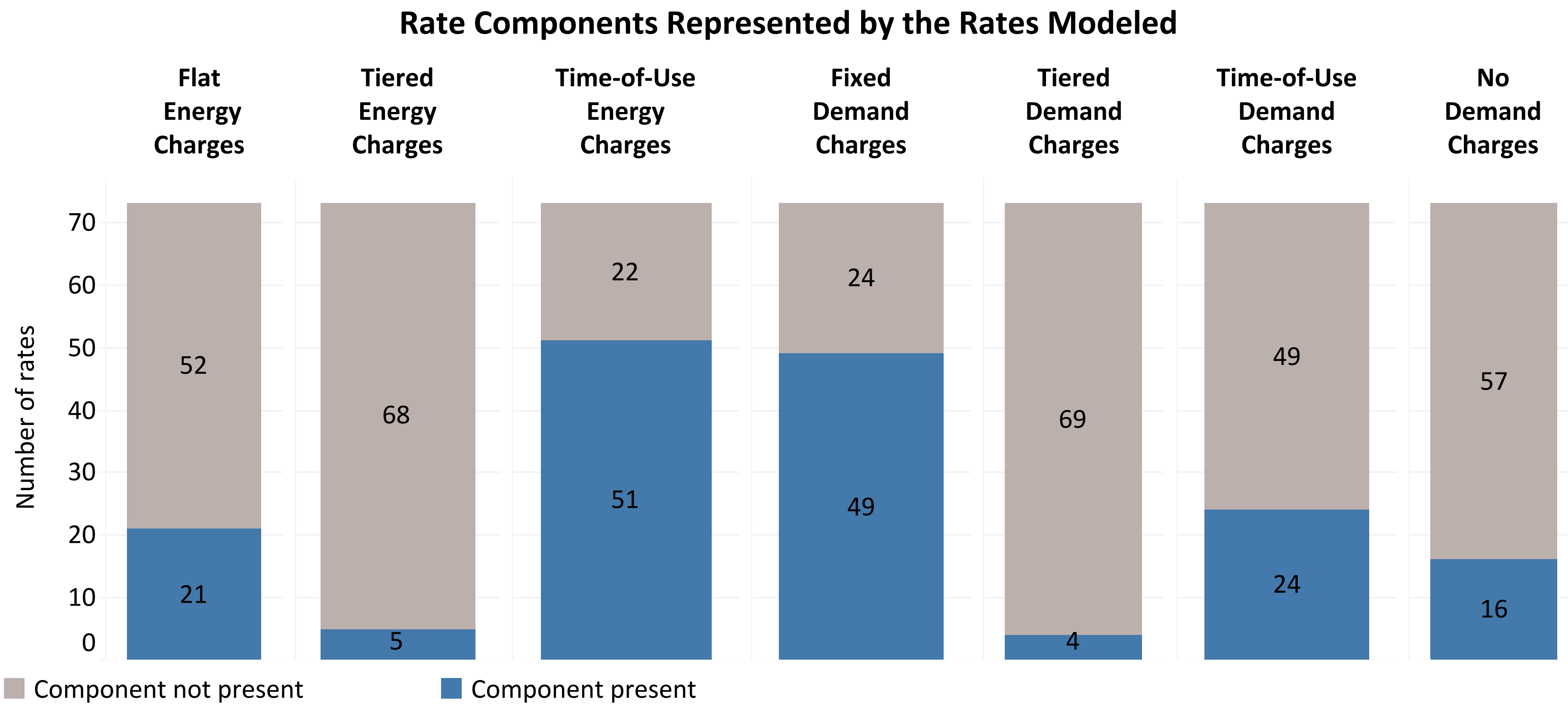
Examples of Annual Load Profiles



https://openei.org/wiki/Solar+Storage

Utility Rates Modeled

The 73 utility rates modeled represent a variety of tariff structures. The majority of rates had demand charge elements or time-of-use elements, and some had both. Several flat rates were also modeled. All of the tariffs were taken from NREL's Utility Rate Database and were up to date as of January 2017. Net energy metering (NEM) is not included in the calcuations, even if the utility offers NEM.



Flat Energy Rate - The per kWh charge is independent of the time it is used or amount that is used.
Time of Use - The charge is based on the time of day and/or year the energy is used.
Tiered - Each unit up to a base amount is charged at one amount, and each additional unit used is charged at a higher amount.
Demand Charge - In addition to an energy charge ($ per kWh), there is a charge based on the highest level of demand (kW) over a billing period, typically measured over 15-minute intervals.
Note: Several of the rates are categorized in more than one energy rate or demand charge category. This is because core rate has one type of component while a rider of the same rate has a different type of component.

Solar PV and Storage Price Assumptions (Cost Points) Used in Cost-optimization Modeling

In order to understand the impact of technology cost on solar and storage economics, multiple cost points were modeled for each scenario (building type and location combination). Each cost point represents the installed cost of solar and storage technologies (including hardware, engineering, labor, and O&M costs). The REopt model selects the cost-optimal size of solar and/or battery system for each scenario, based on these project cost inputs and the other input variables (e.g. financing, rate structure, building load, etc.). Detailed lists of the elements included in the cost inputs below and other modeling inputs and assumptions are provided at the end of this publication.

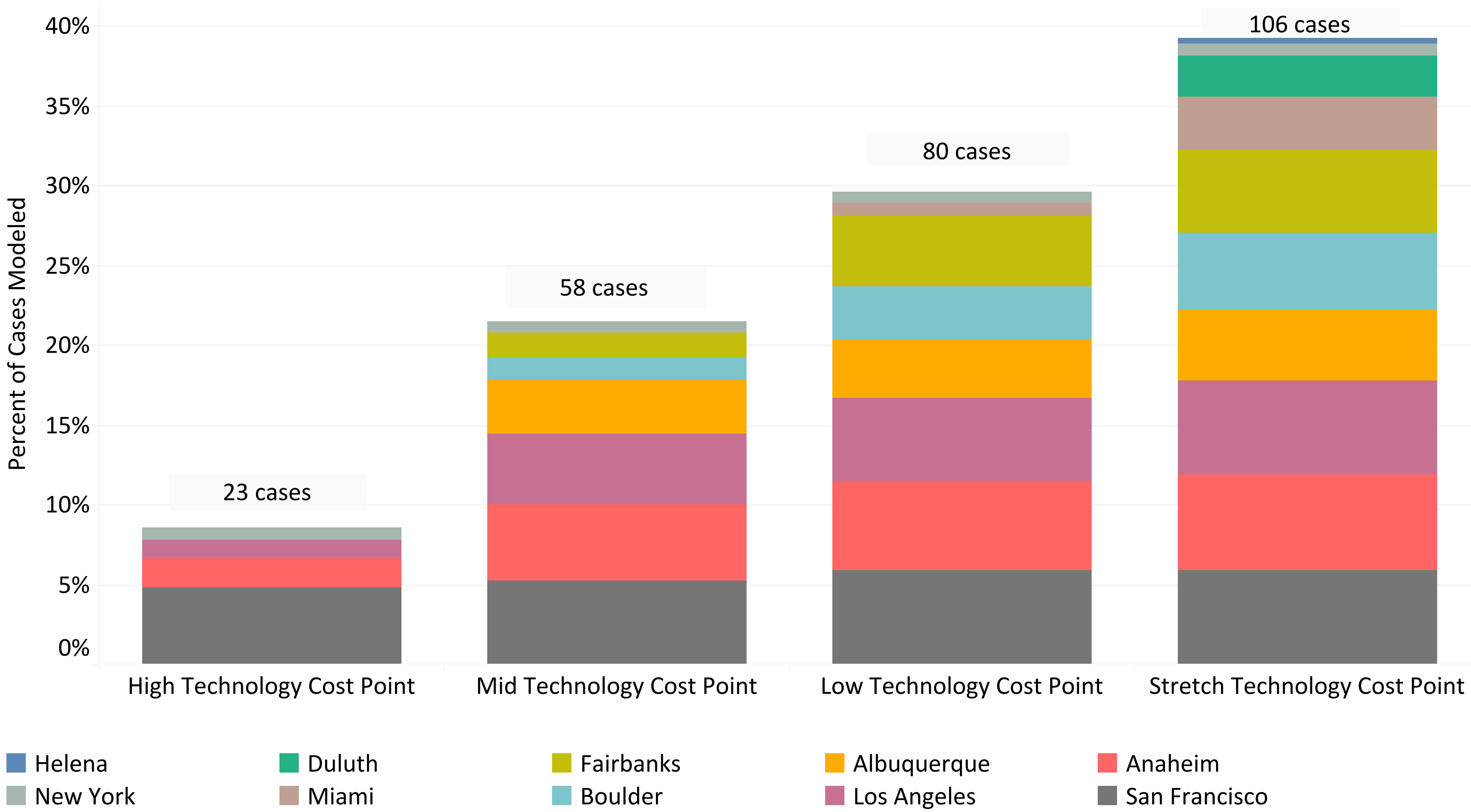
Cost Point	PV System Installed Cost ($/kW)	PV O&M Cost ($/kW)	Battery Storage System Installed Cost for Power Rating* ($/kW)	Battery Storage System Installed Cost for Energy Rating ($/kWh)	Battery Storage Replacement Cost ($/kW)	Battery Storage Replacement Cost ($/kWh)
High Cost Point	$1.37	$8	$1,332	$290	$441	$256
Mid Cost Point	$1.11	$8	$1,062	$256	$407	$238
Low Cost Point	$0.97	$8	$1,193	$151	$326	$106
Stretch Cost Point	$0.90	$8	$787	$106	$276	$97

*Battery storage project costs vary depending on the power to energy ratio (also referred to as 'duration'). The REopt model requires storage project costs to be input as two separate numbers, one for the power rating and another for the energy rating. These two cost variables are considered together in determining the optimal battery system configuration and, hence, the final project cost.

Results

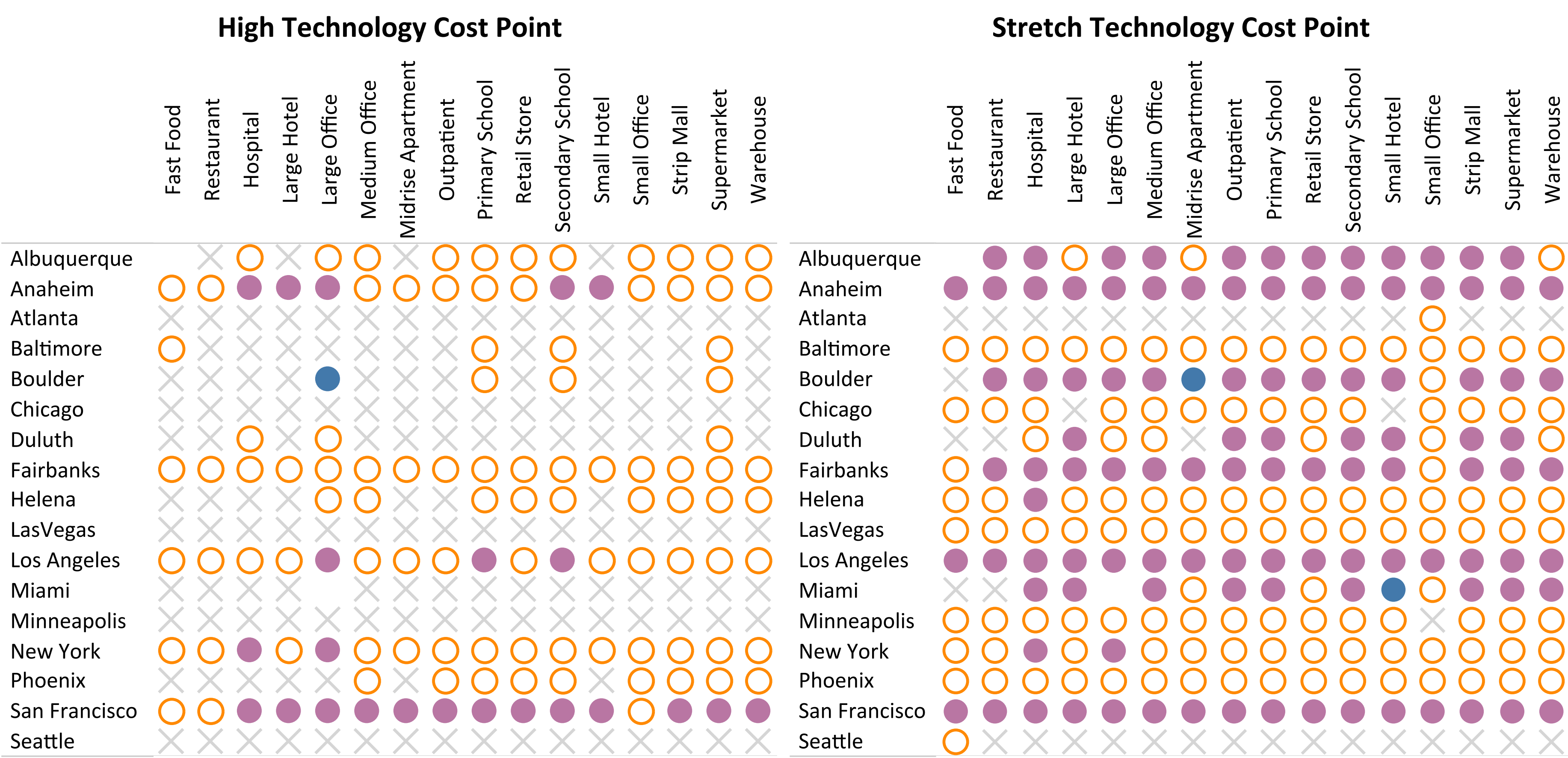
Impact of Technology Cost Reductions on Solar + Storage Economics by Location

As solar and battery costs decline, solar with storage projects become economical in 10 of the 17 locations.



Cost Effective Technology Combinations by Location and Building Type

At the higher technology cost point, solar-only systems are already economical in many locations and building types.
As technology costs decline, solar combined with storage becomes economical in more locations and building types.

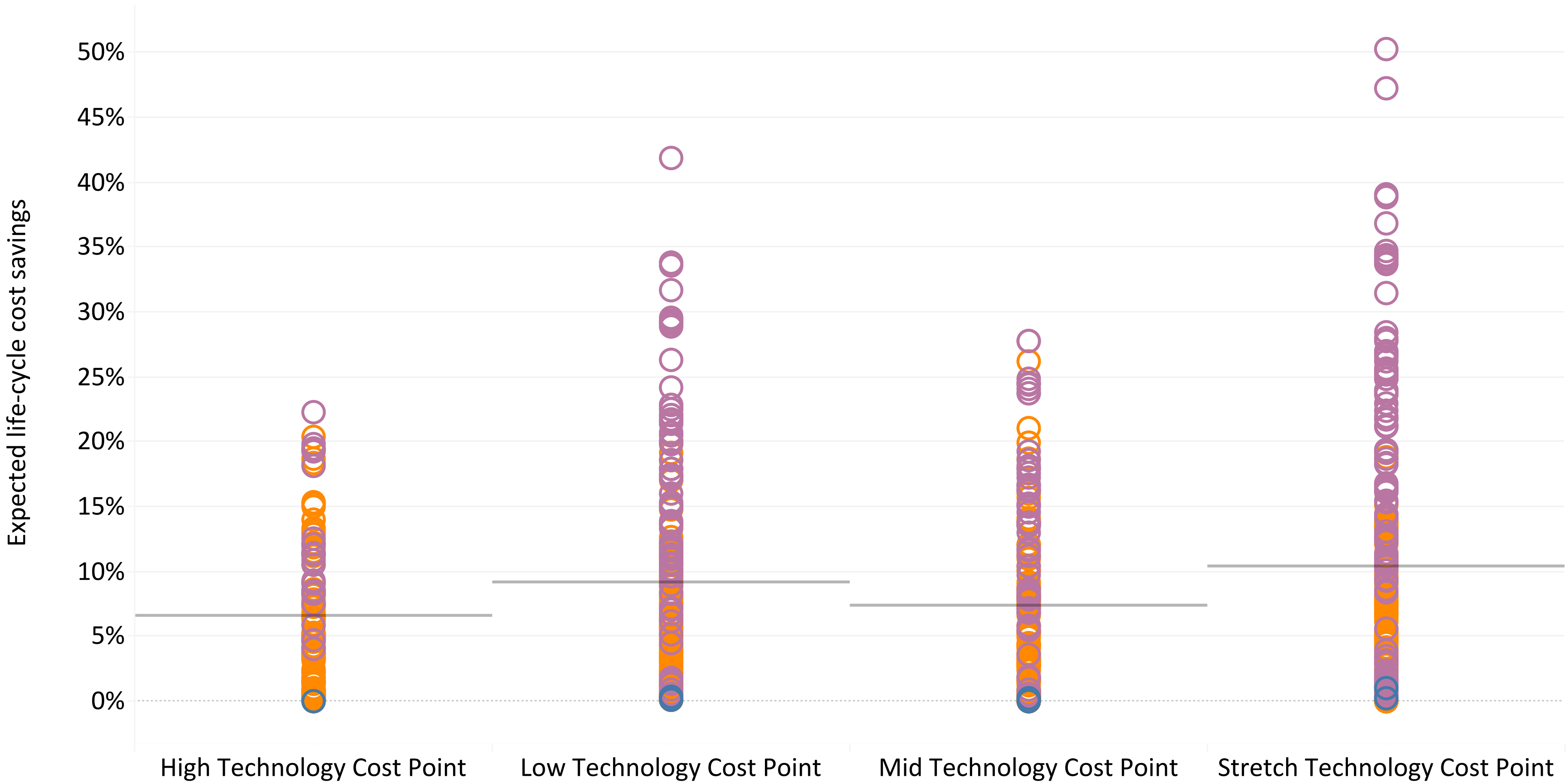


Note: Missing icons indicate no data is available because the load for the reference building was not eligible for any of the rates modeled for that location.

Not Economical | Solar Only | Solar+Storage | Storage Only

Impact of Technology Cost Reductions on Expected Savings

As costs decline, systems become economical for more locations and building types, and the average expected cost savings across all scenarios (indicated by grey line) increases slightly.



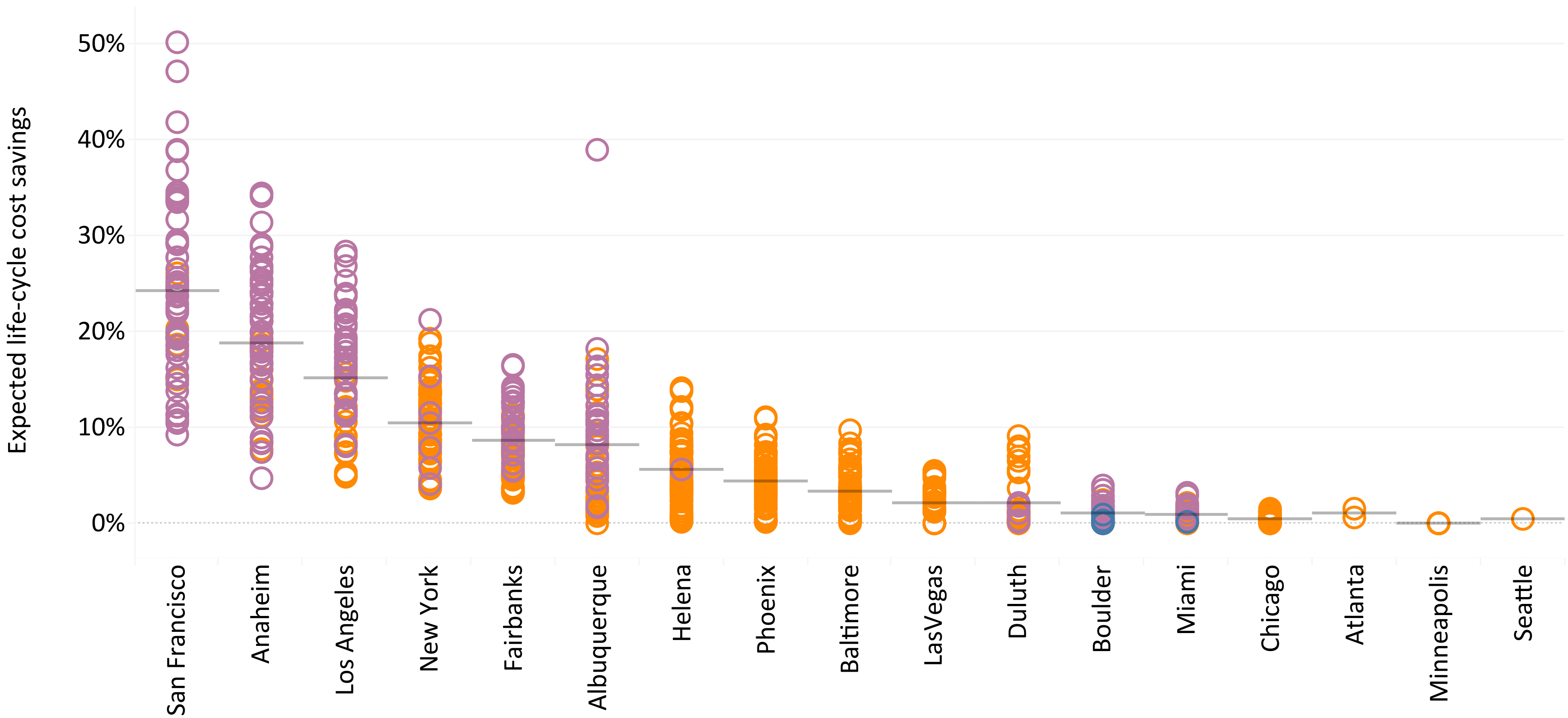
Each line on the chart represents one of the individual cases modeled (e.g., one building type in one location).

Storage Only   Solar+Storage   Solar Only

https://openei.org/wiki/Solar+Storage

Impact of Location on Expected Savings

Location has a notable impact on expected savings from solar and storage systems, likely due to the variation in rate structure and electricity price across locations. Across all scenarios modeled, solar-with-storage systems were most often cost effective in San Francisco, Anaheim, and Los Angeles. Solar-with-storage also was found cost effective in some buildings in Fairbanks, Albuquerque, Boulder, and Miami. Solar-only projects provided savings in many of the other locations.

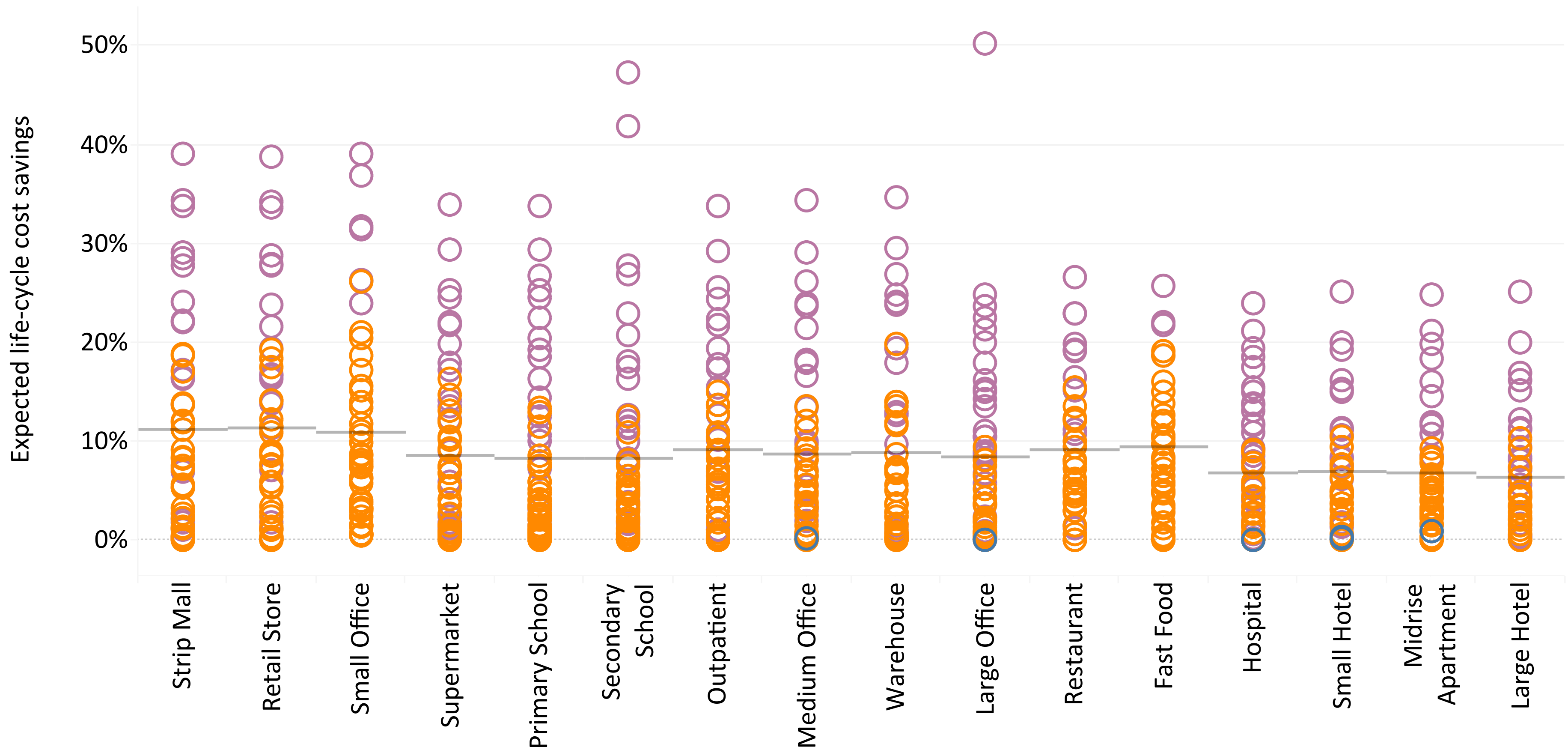


Each line on the chart represents one of the individual cases modeled (e.g,. one building type in one location).

Storage Only   Solar+Storage   Solar Only

Impact of Building Type on Expected Savings

Solar combined with storage was found to provide cost savings in every building type, and solar-only projects were economical in many additional scenarios. The percent savings is less variable across building type than across location, indicating that the building load profile may have less influence on savings potential than other variables, such as rate structure.

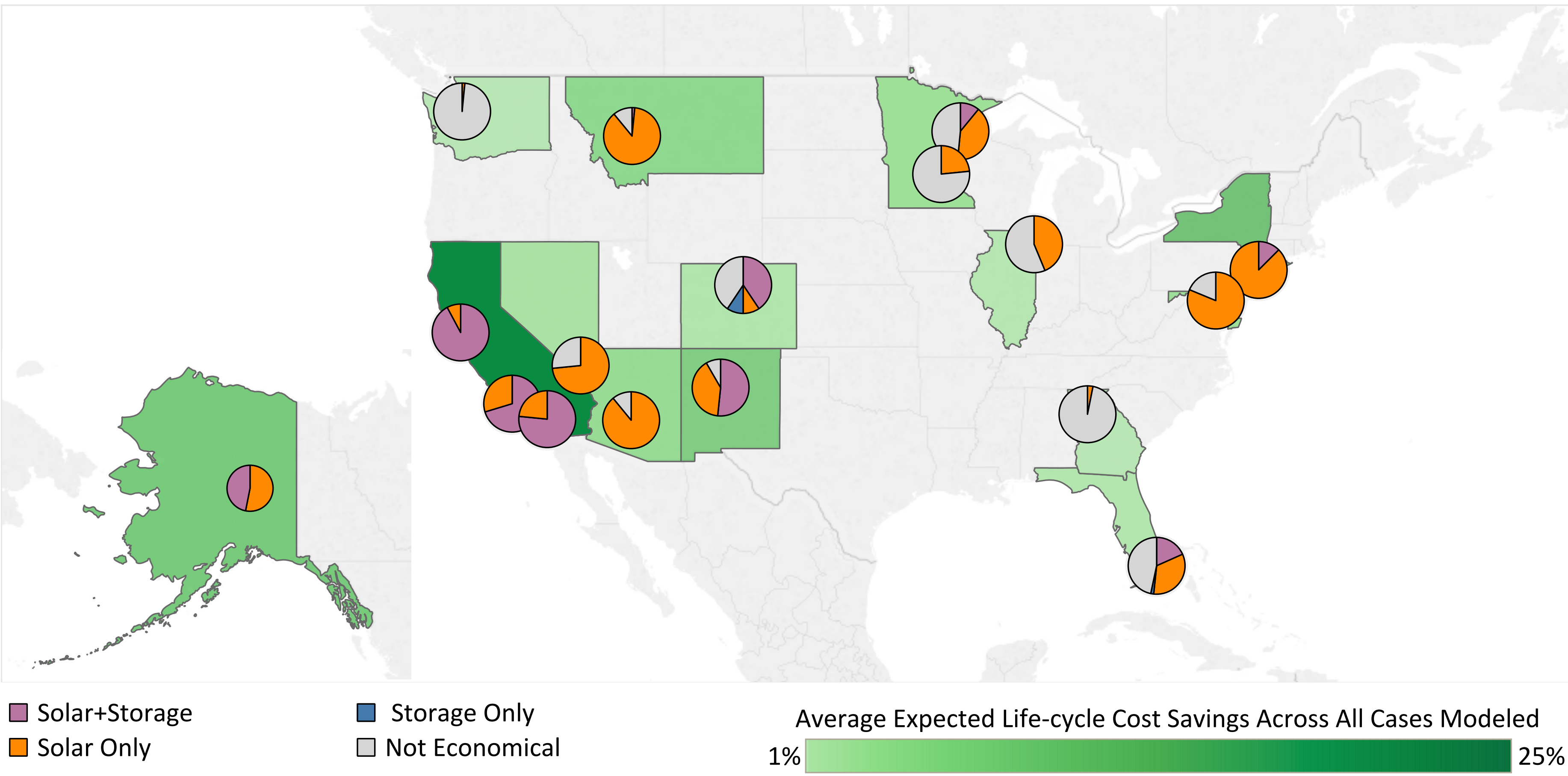


Each line on the chart represents one of the individual case modeled (e.g., one building type in one location).

Storage Only   Solar Only   Solar+Storage

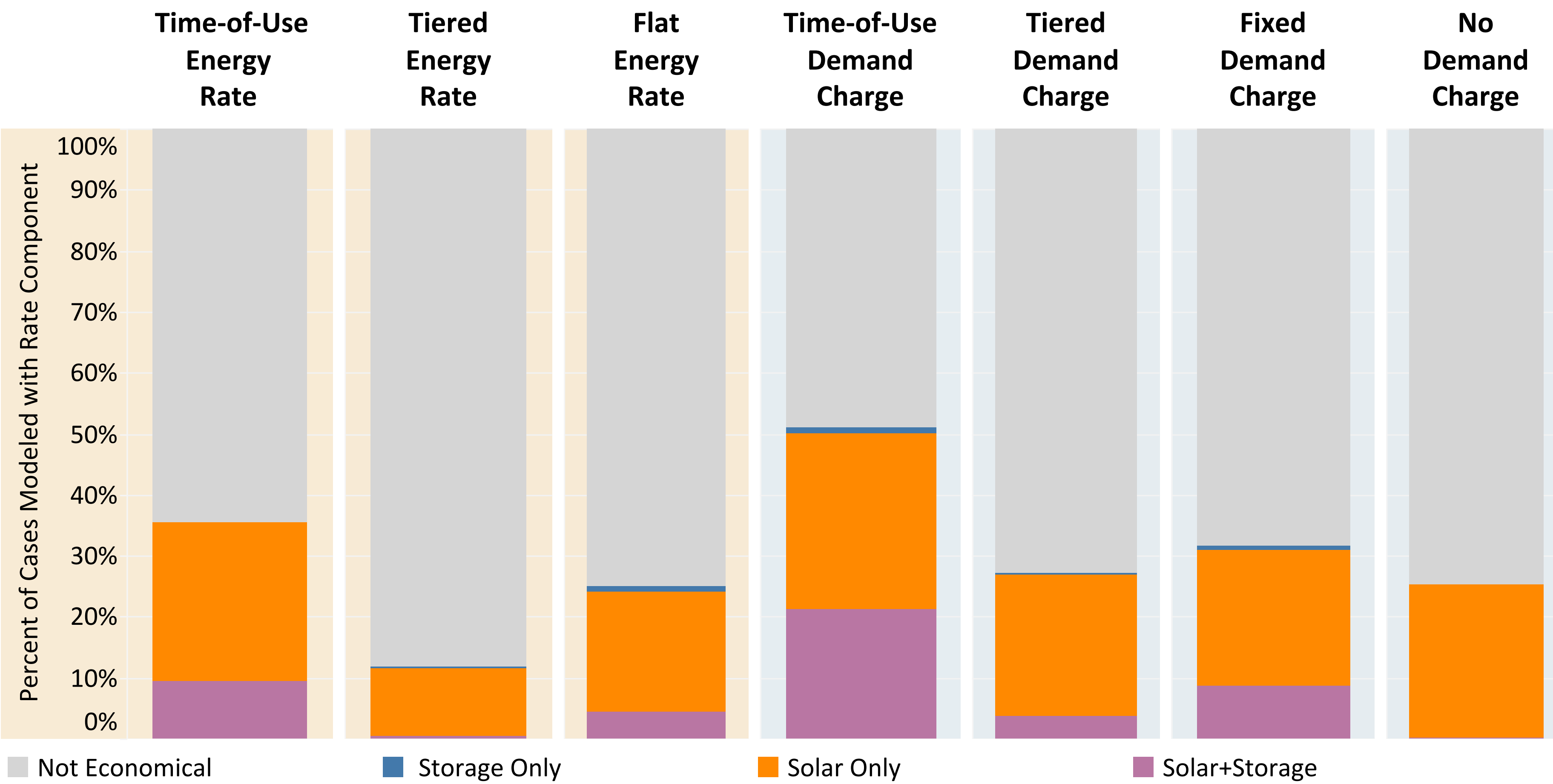
Average Potential for Savings from Solar or Solar + Storage in Commercial Buildings for Locations Modeled

The map below summarizes the results for all buildings and locations modeled. The darker-shaded states were found to have higher potential for savings. The pie charts indicate the degree to which each technology combination contributed to the cost reduction. Savings were highest in California, New York, New Mexico, and Alaska. Solar alone was economical for some of the building types in every location, while solar combined with storage provided cost savings in more than half of the locations. Some states, such as Georgia and Washington, had few cases in which solar and/or storage was found to provide savings potential.



Impact of Rate Structure Components on Cost-Optimal Technology Combination

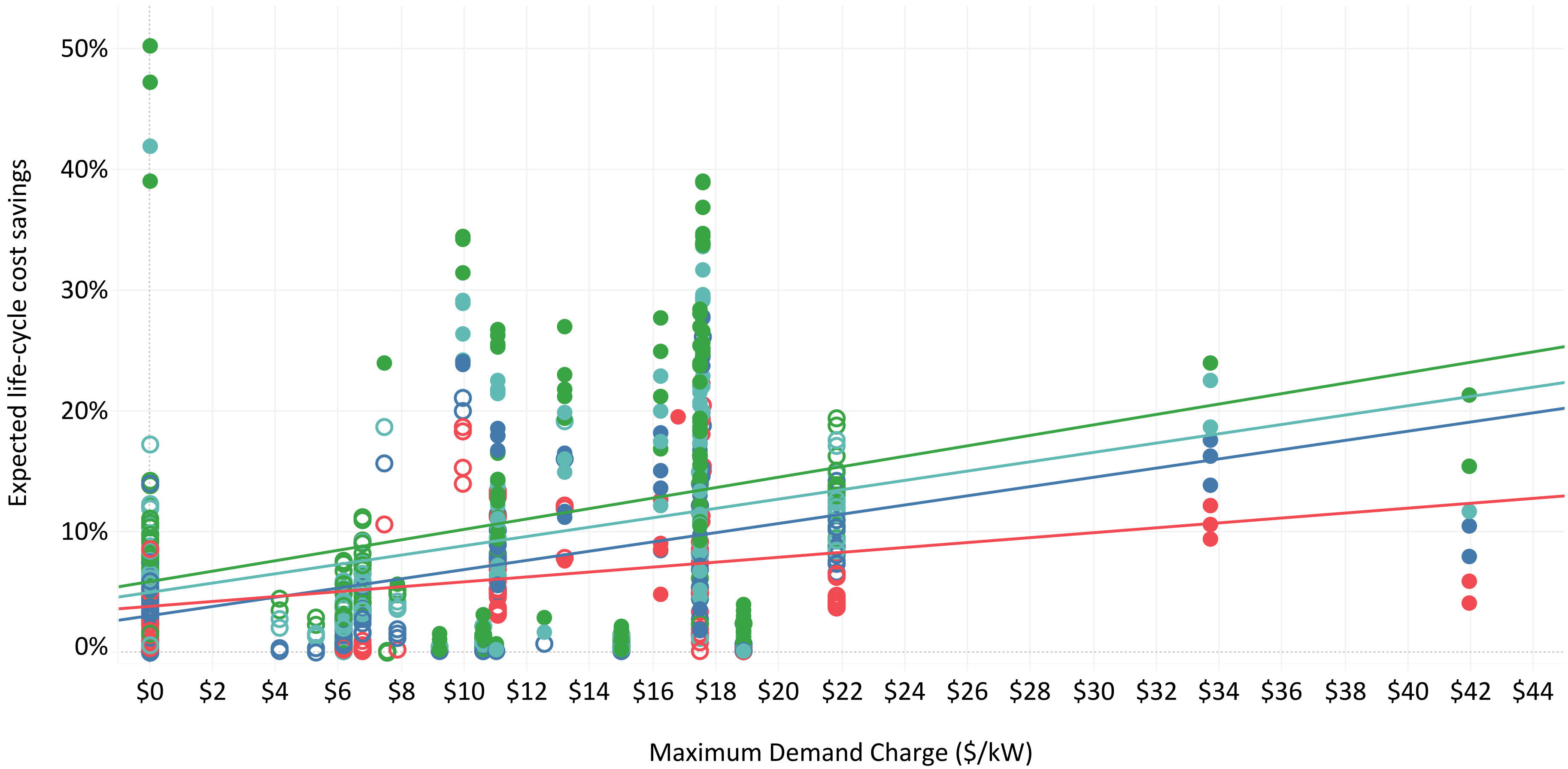
Across the scenarios modeled, solar combined with storage is more likely to be economical under demand charges and under rates with time-of-use components.



Rate components are not mutually exclusive. A typical commercial rate consists of an energy component (kWh) and a demand charge component (kW).

Impact of Demand Charge Level and Technology Cost on Expected Percent Savings

Projects that include storage are most frequently economical at demand charge levels > $10, regardless of technology cost. As technology costs decline, the expected percent savings across all projects increases.

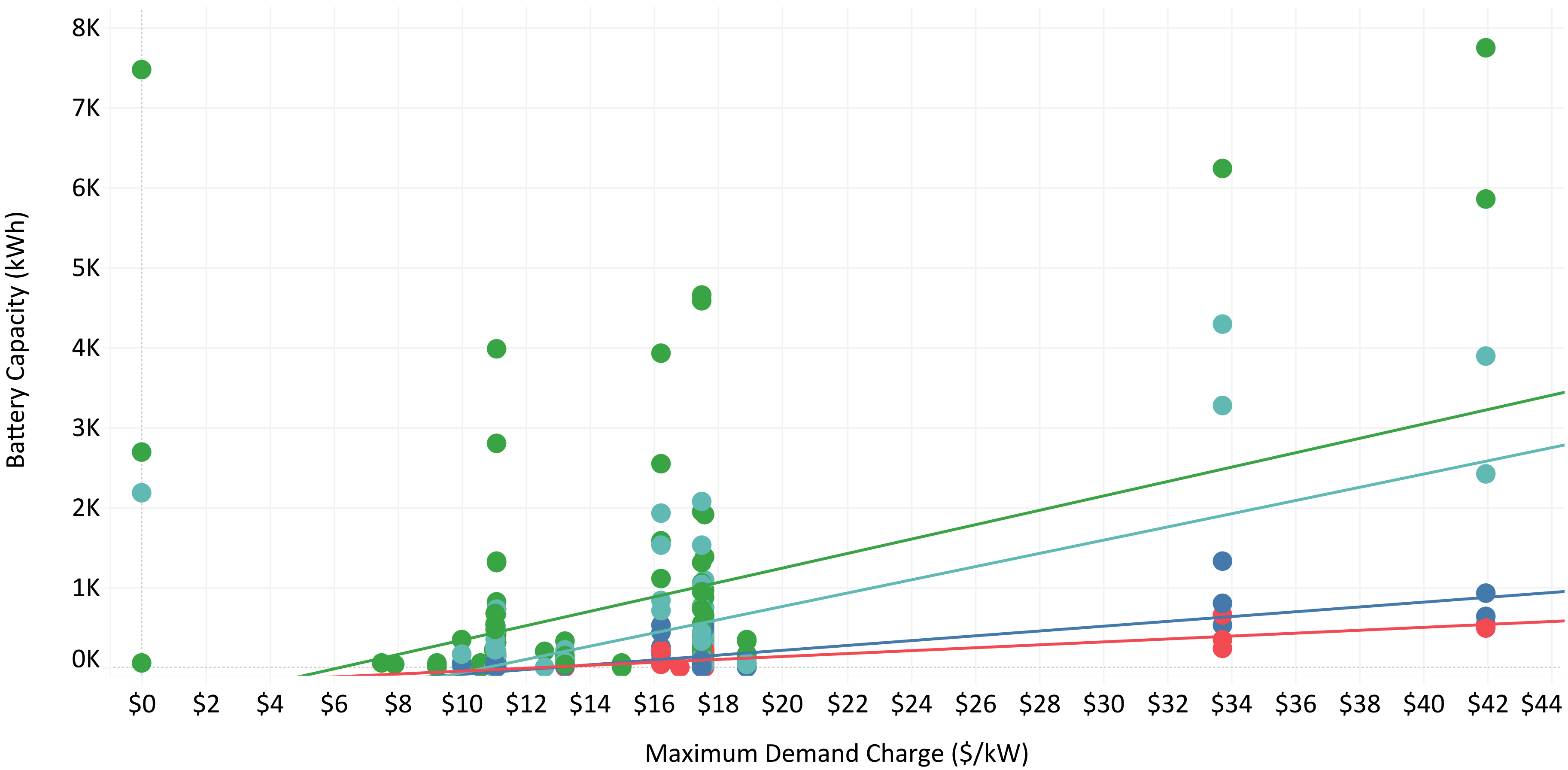


Each point on the chart represents one of the individual cases modeled (e.g., one building type in one location).

High Technology Cost Point
Low Technology Cost Point
Mid Technology Cost Point
Stretch Technology Cost Point
● Storage Only
● Solar+Storage
○ Solar Only

Impact of Demand Charge Level and Technology Cost on Optimal Battery Capacity

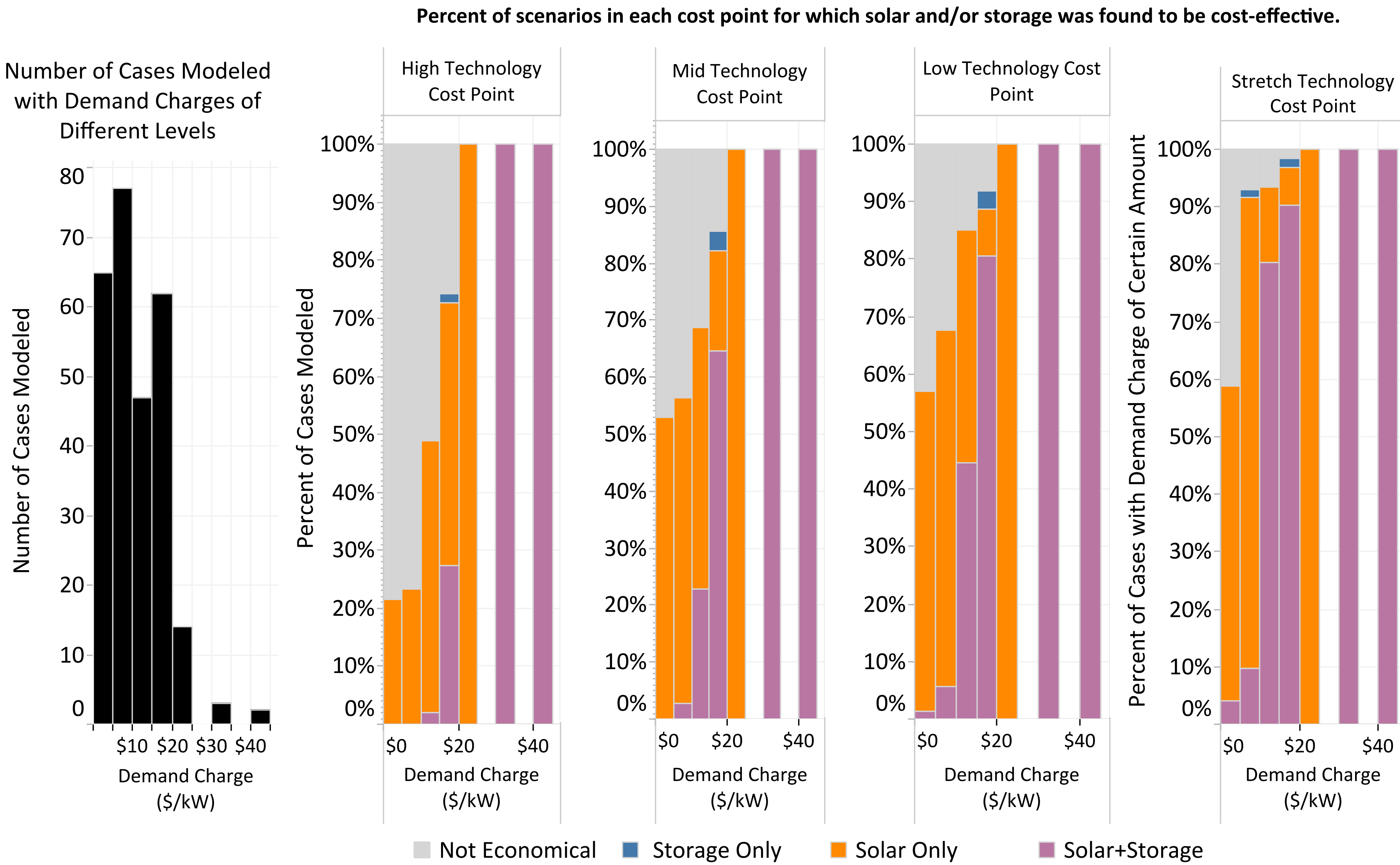
Optimal battery capacity increases under higher demand charges and falling technology costs.



Each point on the chart represents one of the individual cases modeled (e.g., one building type in one location). Cases for which no battery was built are filtered out.

Impact of Demand Charge Level and Technology Cost on Solar and Storage Economics

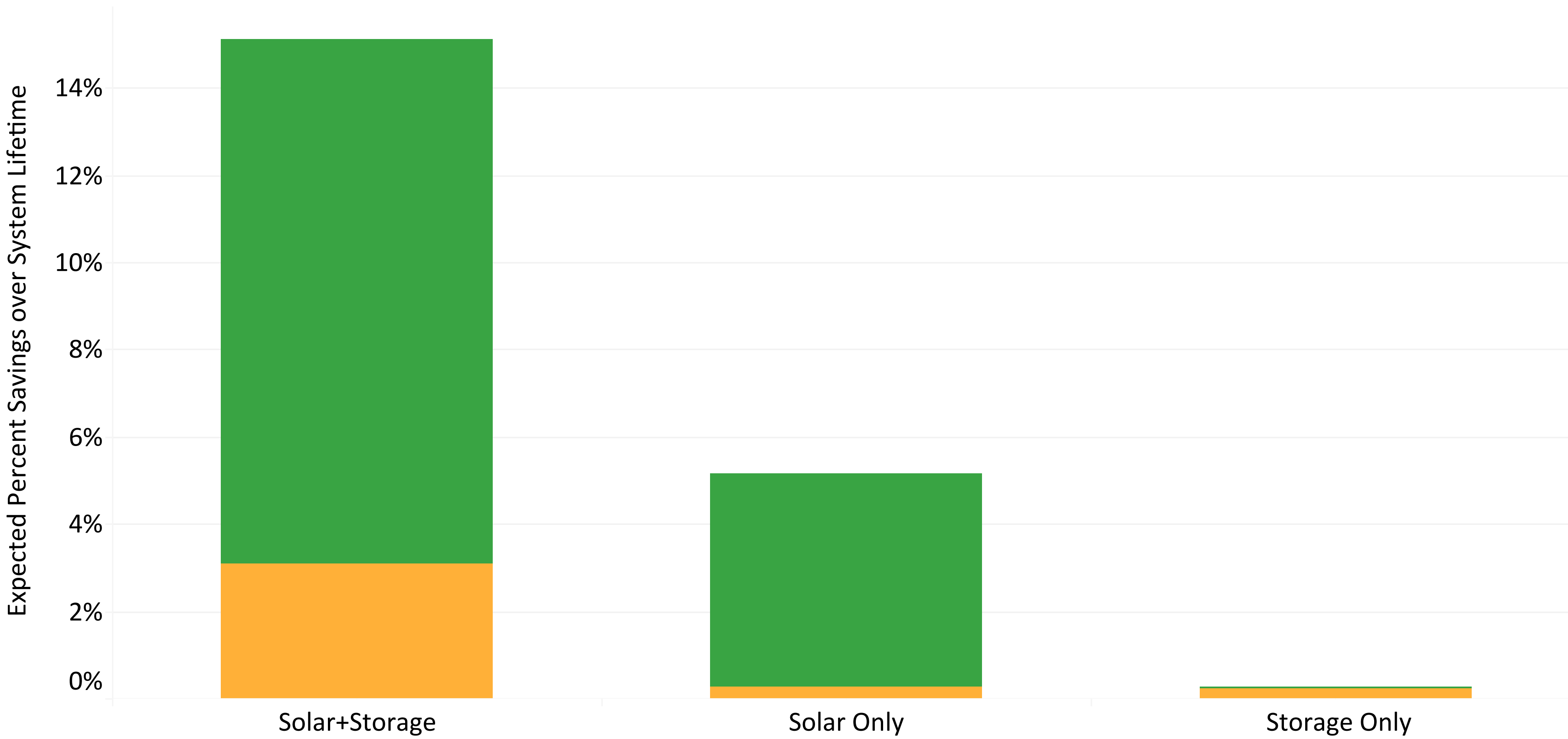
As technology prices drop, solar-with-storage becomes economical in more cases and at lower demand charge rates.



https://openei.org/wiki/Solar+Storage

Savings from Demand Charge Reductions versus Energy Charge Reductions by Technology Combination

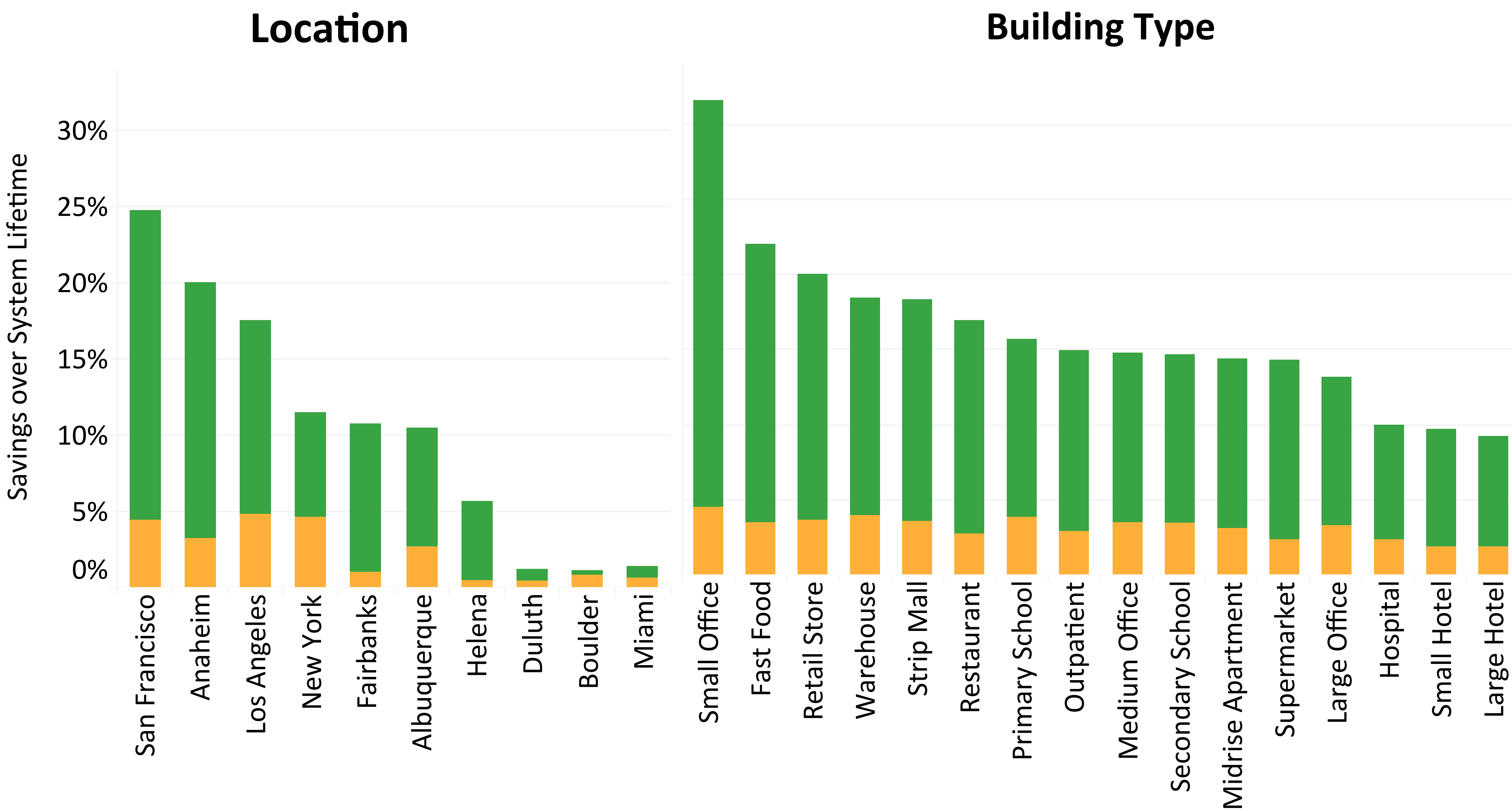
On average, savings were highest for projects that combined both solar and storage. The majority of savings from both solar-only and solar with storage projects were derived from reductions in energy charges. The limited number of storage-only projects resulted in mostly demand charge savings, though savings were marginal.



Average of all locations, building types and cost points modeled.

https://openei.org/wiki/Solar+Storage

Savings from Demand Charge Reductions versus Energy Charge Reductions by Location and Building Type

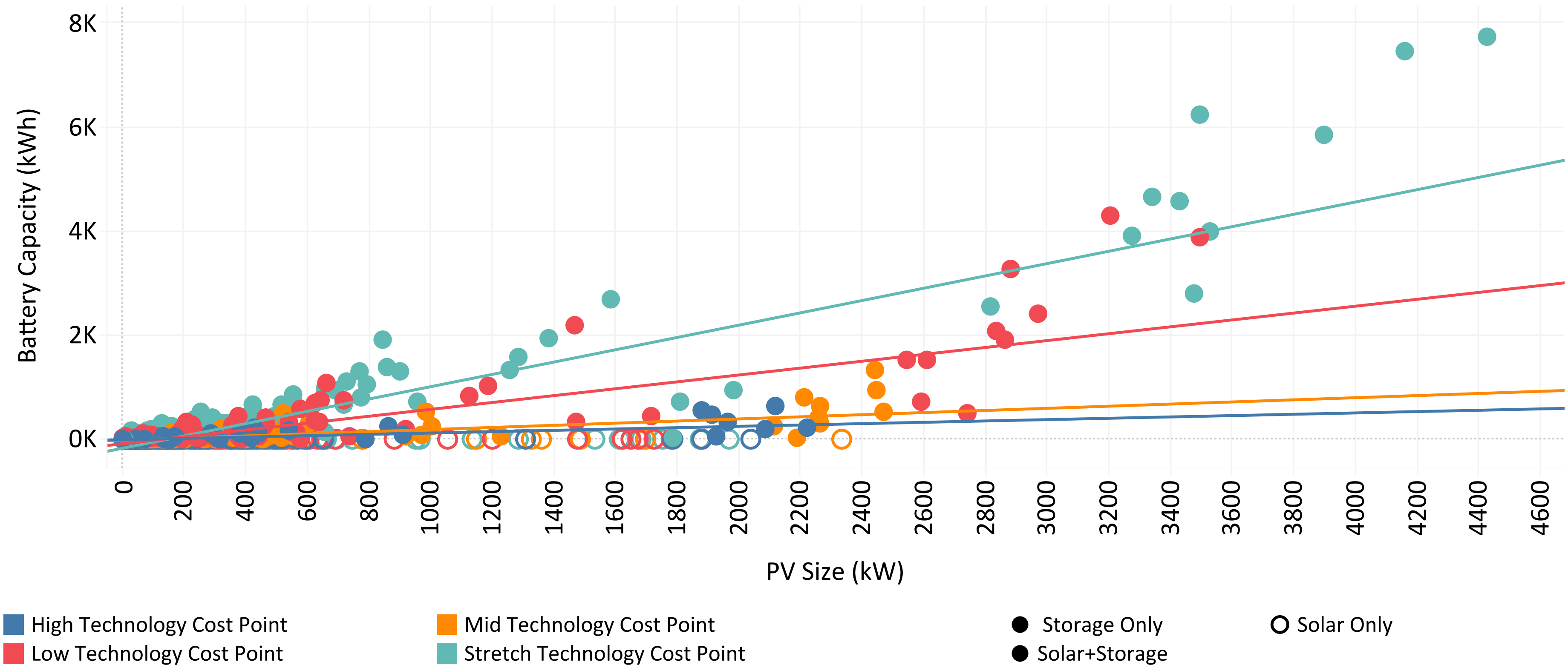


Note: Includes results for projects that include storage. Average of all cost points modeled.

$/kWh Savings $/kW Savings

Impact of Cost Declines on System Sizes

Average system sizes increase with declining costs.



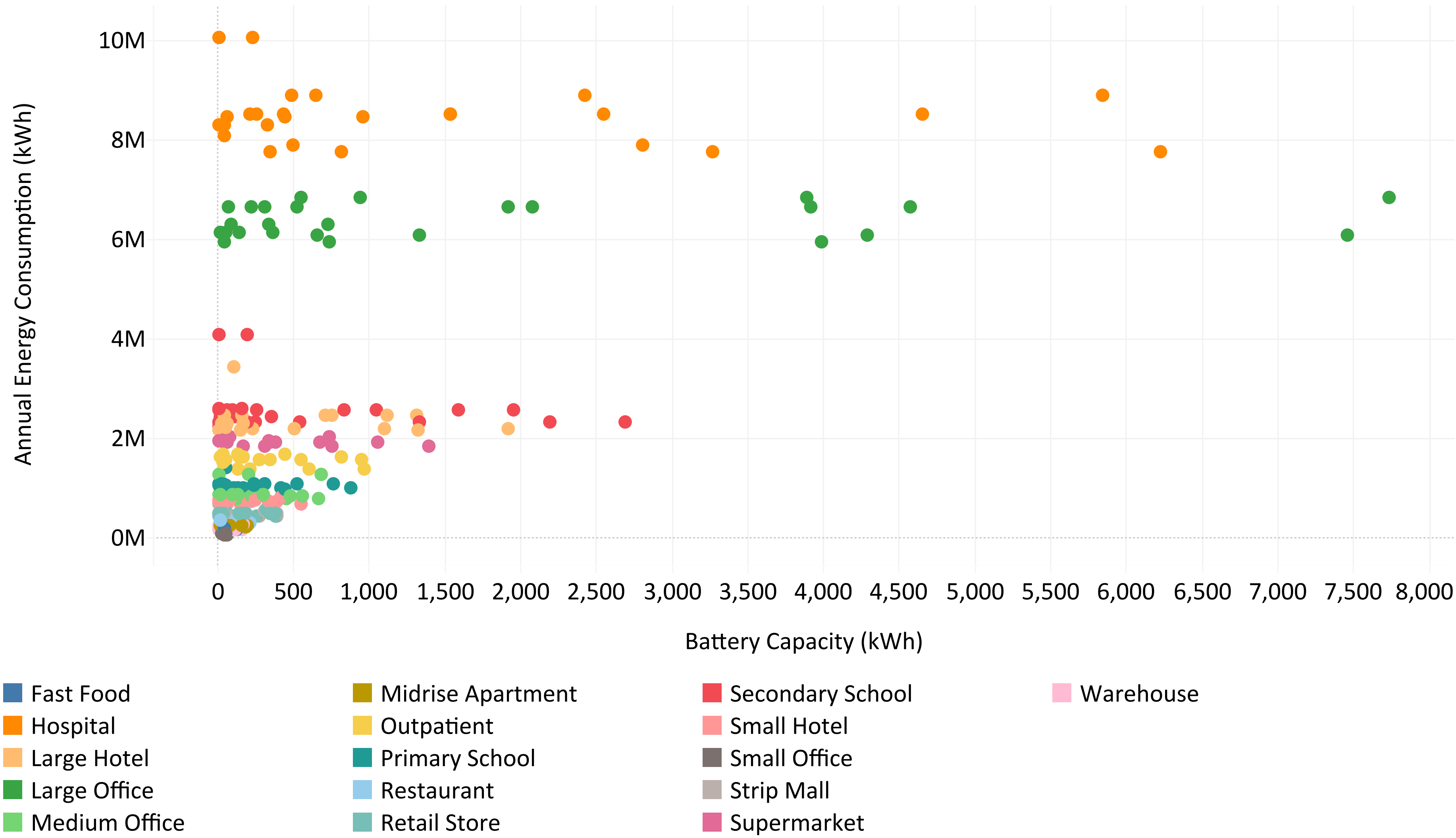
Average System Sizes and Capital Costs Across All Buildings and Locations

	High Technology Cost Point	Mid Technology Cost Point	Low Technology Cost Point	Stretch Technology Cost Point
PV Size (kW)	156 kW	239 kW	324 kW	408 kW
Battery Power (kW)	6 kW	12 kW	27 kW	51 kW
Battery Capacity (kWh)	15 kWh	35 kWh	146 kWh	329 kWh
Capital Cost of All Projects ($)	$113,593	$146,192	$189,828	$232,723
Capital Cost of Solar-only Projects ($)	$53,973	$66,256	$91,430	$117,614
Capital Cost of Solar+Storage Projects ($)	$390,458	$311,516	$358,018	$366,250
Capital Cost of Storage-only Projects ($)	$131,724	$107,352	$120,563	$131,682

https://openei.org/wiki/Solar+Storage

Impact of Building Energy Consumption on Economic System Sizes

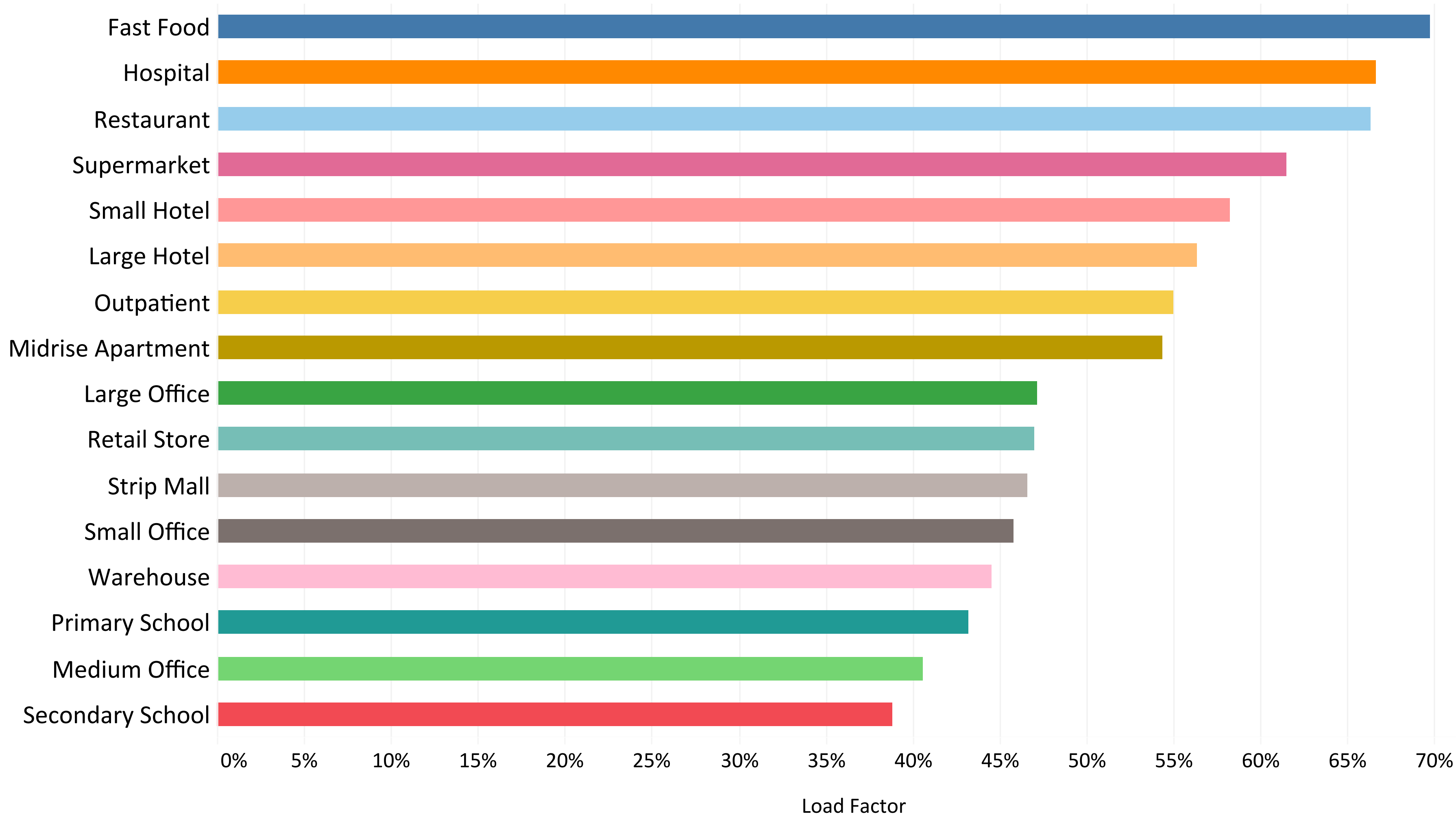
Optimal battery capacity increases with building load, especially at lower technology costs. The largest battery systems were cost effective in hospitals and large offices.



https://openei.org/wiki/Solar+Storage

Load Factors

Load factor indicates the degree of fluctuation in the building load. It is calculated by dividing the mean demand by the peak demand over the course of a year. A low percentage indicates higher variability in the load. The chart below shows the load factors of the buildings modeled.



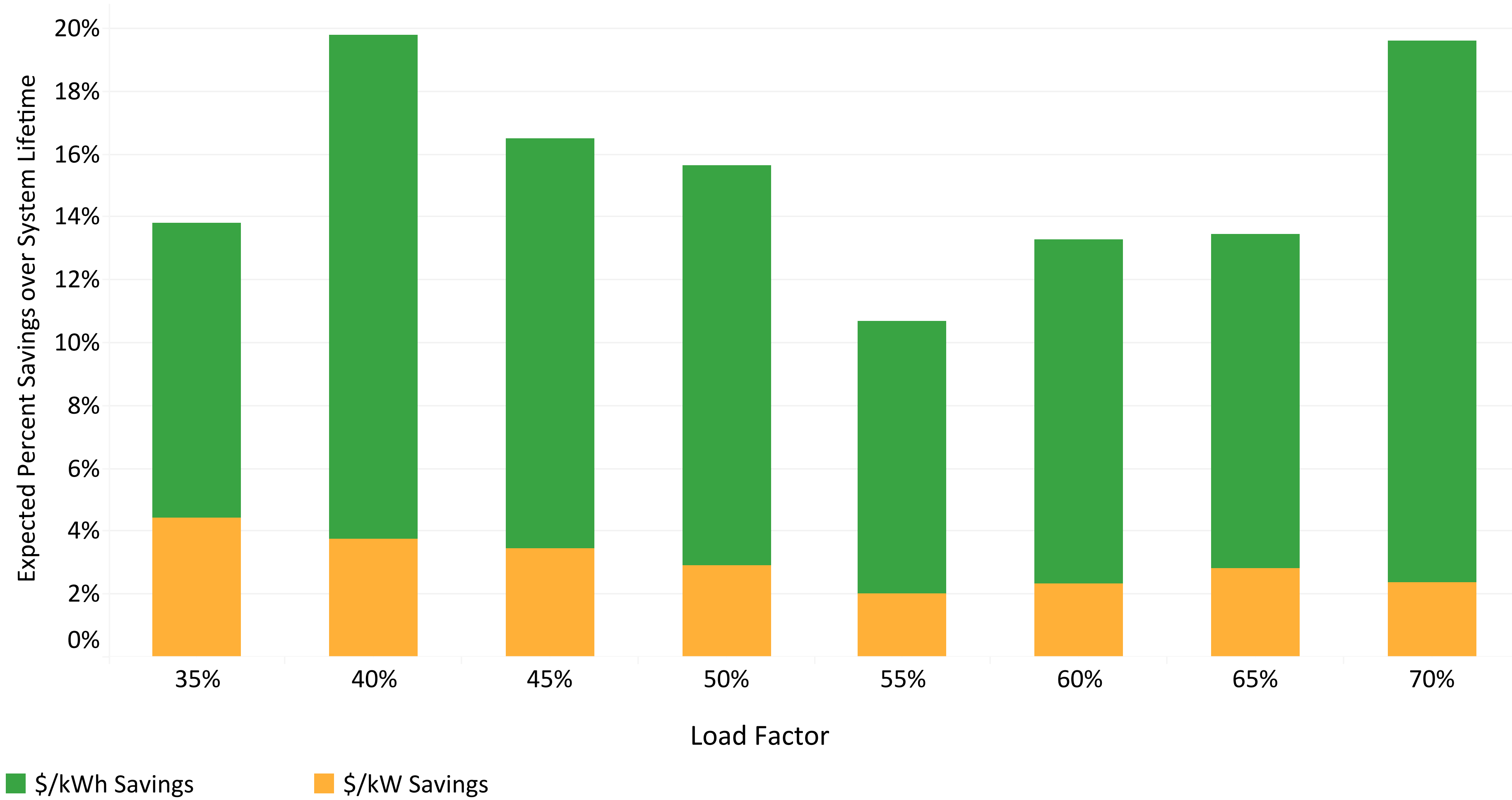
Impact of Load Variability on Expected Savings

A common assumption is that load profiles with peaks are the most likely candidates for savings from storage due to the opportunity for demand charge reduction. Our results indicate that by combining solar with storage, buildings with less variability may also achieve savings. This is likely due to the energy cost reductions resulting from the solar generation.

https://openei.org/wiki/Solar+Storage

Impact of Load Variability on Expected Savings from Solar Combined with Storage

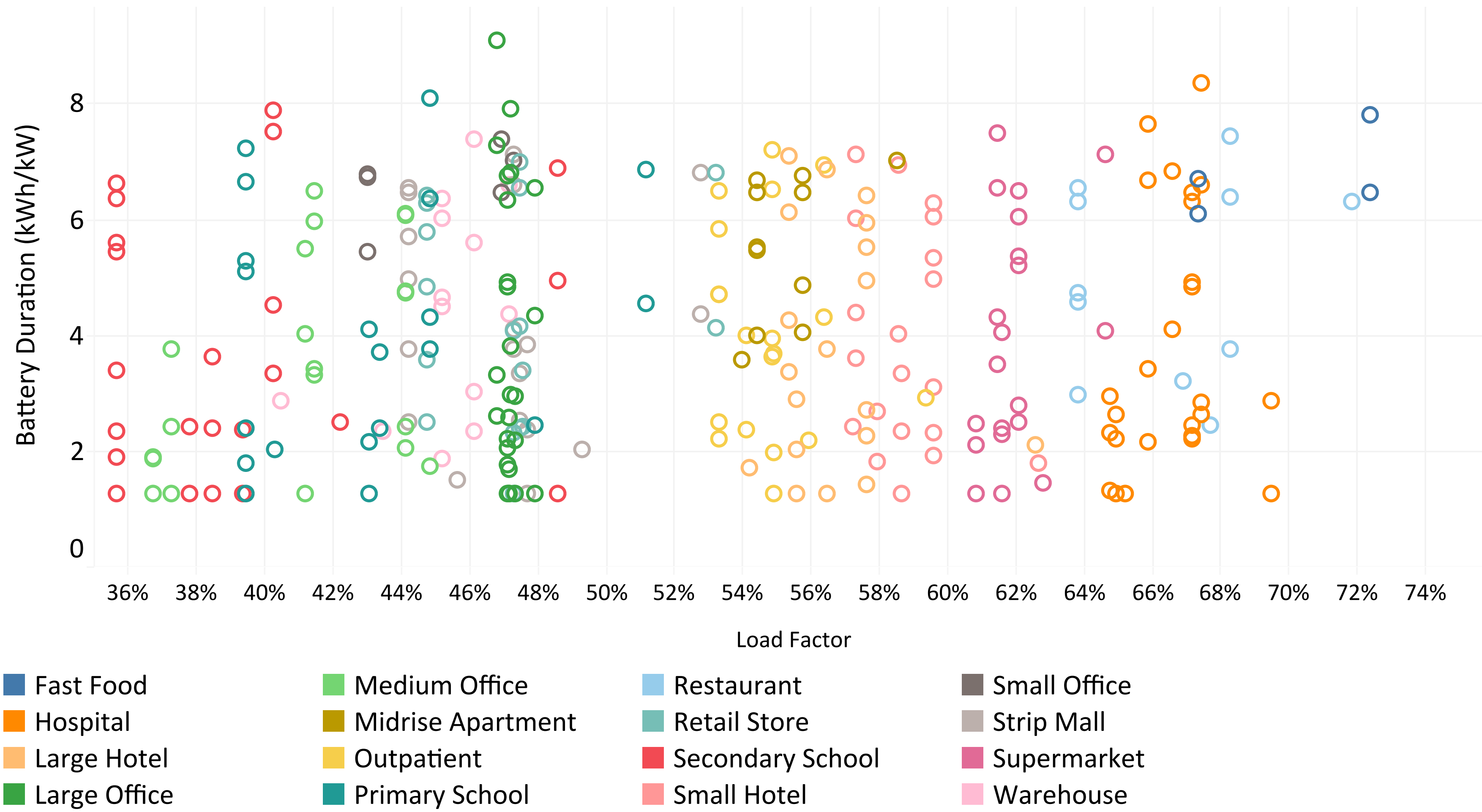
Breaking out energy charge and demand charge savings by building load factor shows the extent to which variability in the load impacts savings. Demand charge savings are higher in cases with more variability in load profile; however, total savings from combined solar and storage projects is not related to load variability.



https://openei.org/wiki/Solar+Storage

Impact of Load Variability on Battery Configuration

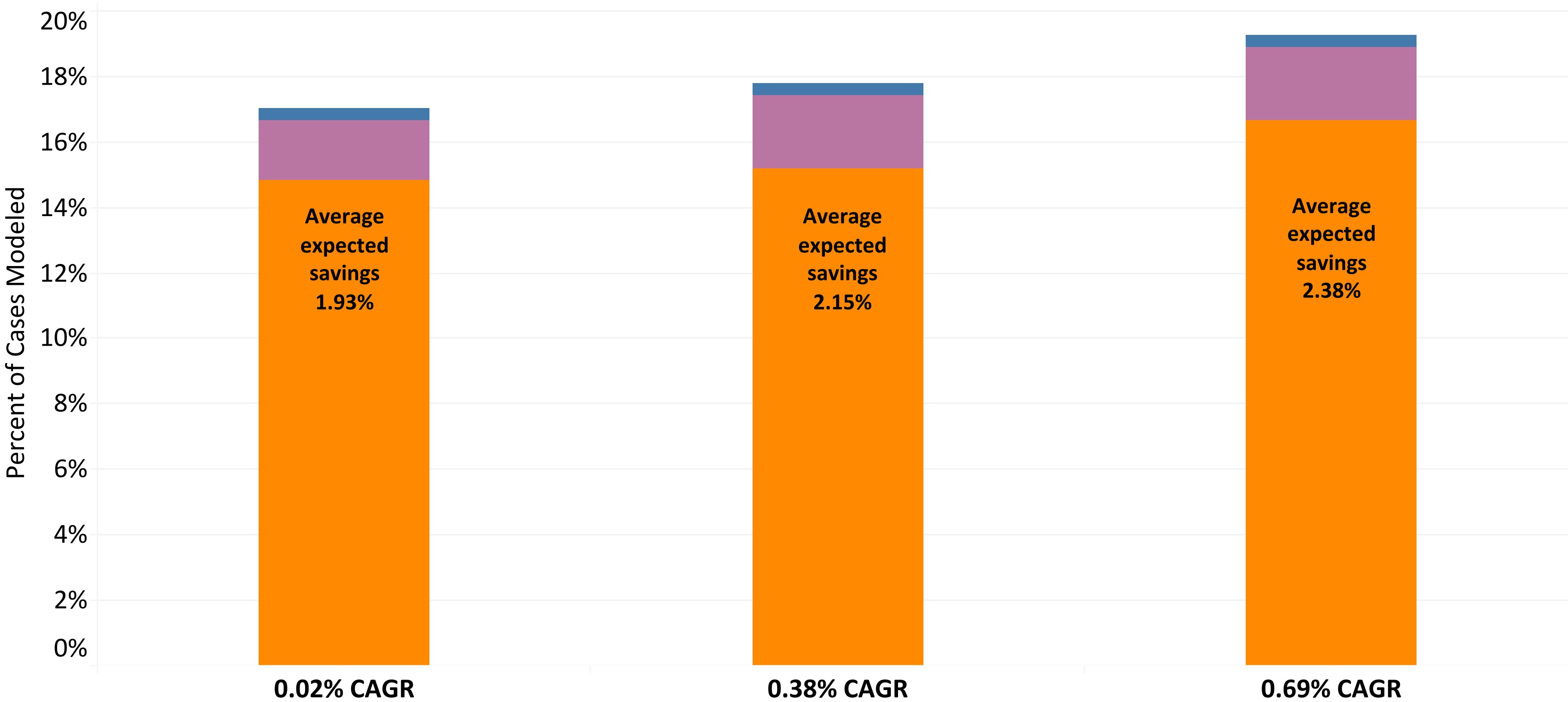
No relationship was found between load variability and the battery configuration. Optimization modeling resulted in vastly different battery durations for buildings of the same type and of similar load variability. Other variables, such as technology cost and rate structure, were more influential on the cost-optimal battery sizing and duration.



https://openei.org/wiki/Solar+Storage

Impact of Electricity Price Increases on Expected Savings from Solar and/or Storage Systems

Varying electricity prices (compound annual growth rates) have little impact on expected savings. Across all scenarios modeled, low annual electricity price growth of 0.02% resulted in economical systems in 17% of the cases, while high annual price growth of 0.69% resulted in systems being economical in about 19% of the cases.

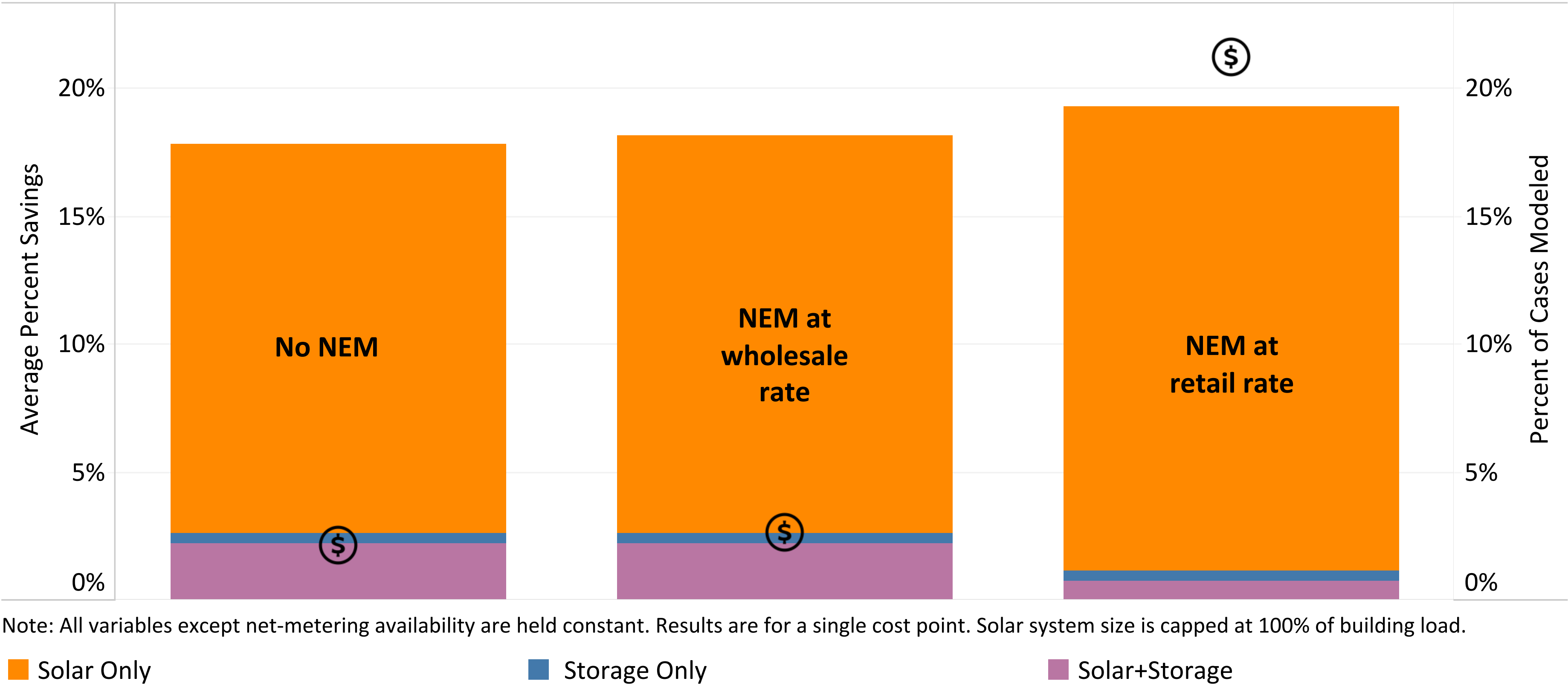


Note: All variables except compound annual growth rate of electricity are held constant. Results are for an average of all cost points.

Impact of Net-Metering Policy on Solar and Storage Economics

Net energy metering (NEM or net-metering) is not included in the results presented in the other slides of this report. NEM is not available in all locations and NEM offerings continue to evolve. When NEM is available, the grid serves the same purpose as a battery. When net-metering is not available, storage projects are found to be economical in more cases. The chart below shows that reduction of the net-metering rate from a retail to wholesale rate also stimulates storage. Averaging across all locations and building types for one cost point, the average expected lifetime savings is highest when net-metering is available.

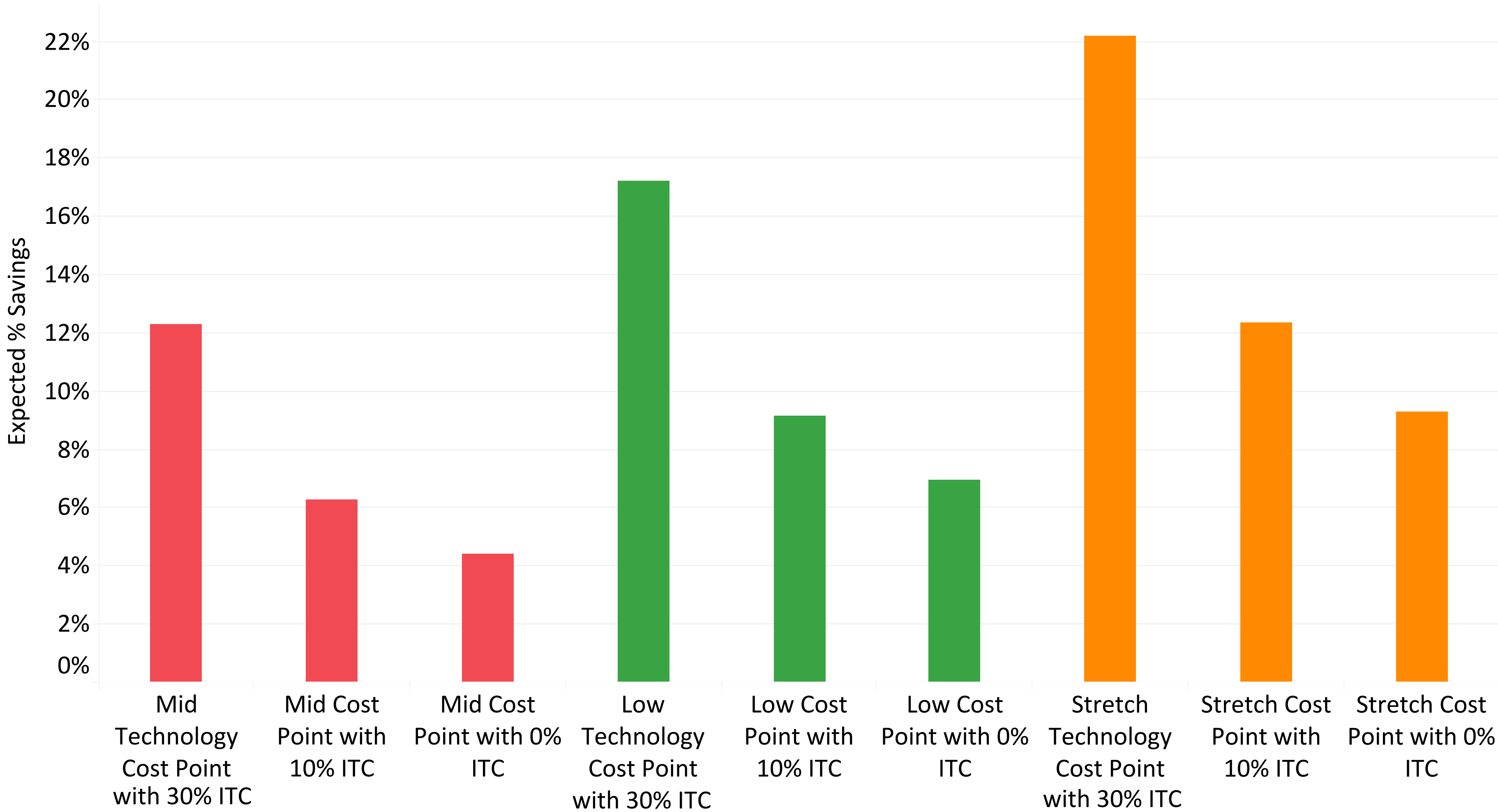
Percent of Cases Modeled with Economic Technology Combinations and Average Percent Savings



Note: All variables except net-metering availability are held constant. Results are for a single cost point. Solar system size is capped at 100% of building load.

Impact of ITC on Expected Savings

The graph below compares the average expected savings from solar and/or storage systems under different tax credit sensitivities and technology costs. Averaging across all building types and locations, expected near-term or stretch goal technology cost reductions do not make up for a complete removal of the investment tax credit (ITC).



Modeling Assumptions

Renewable Energy Optimization Model (REopt)

NREL's Renewable Energy Optimization Model (REopt), which provides site-specific cost-optimal technology solutions, was used for this analysis.

REopt is a mixed integer linear program that outputs optimal technology sizing and hourly dispatch strategies along with financial data. REopt looks at solar and storage in integration with other energy assets, at a single site or across a portfolio of sites, and calculates system sizes and operating strategies to maximize economic benefit.

NREL provides analysis services using the full, in-house REopt model. The REopt Lite web tool is a simplified, publicly available tool to evaluate solar photovoltaics and battery storage at a site.

For more information about REopt and to use the REopt Lite tool, visit: https://reopt.nrel.gov/ or email <REopt@nrel.gov>.

Components Included in the Cost Assumptions

Battery & Hardware Costs

Battery (lithium ion)
Inverter - power conversion
Container or housing
Container extras (insulation/walls)
Electrical conduit (inside of container)
Communication device
Heating, ventilation, air-conditioning (HVAC)
Meter (revenue grade)
Fire detection
Fire suppression
Labor
AC main panel
DC disconnect
Isolation transformer
Auxillary power, lighting, etc.

Engineering, Planning & Construction (EPC) Costs

Control system/SCADA
Site preparation
Loading & transport from manufacturer
Lifting & hoisting by crane on site
Professional engineer stamped calculations & drawings
Manufacturer testing and commissioning
Electrical balance of systems outside of container
Electrical labor
Structural balance of systems (e.g., fencing)

EPC Overhead & Profit

Soft costs
Developer cost (customer acquisition)
Interconnection

https://openei.org/wiki/Solar+Storage

Battery and Inverter Assumptions

Inverter & Storage Replacement	In Year 10
Total Round-Trip Efficiency	82.9%
Battery Throughput	85%
Inverter Efficiency	92%
Rectifier Efficiency	90%
Minimum Charge	20%

https://openei.org/wiki/Solar+Storage

Policy and Financing Assumptions

Net Energy Metering (NEM): NOT INCLUDED
The modeling results presented here do not include a provision for net energy metering. NEM is not available in every state, and the policy is under revision or review in some states. A sensitivity analysis is presented that indicates the impact of NEM on system economics.

Investment Tax Credit: Included, 30%
An investment tax credit of 30% for solar technology is included in the calcuations. A sensitivity analysis is presented that indicates the impact of an ITC step-down or removal on system economics.

Modified Accelerated Capital Depreciation (MACRS): 5 year + bonus depreciation for solar and battery system components

No other Federal or State incentives are included in the calculations.

Inflation Rate: 2.5%

System Life: 20 years, battery replacement at year 10

Discount Rate: 10.2%
The assumed discount rate used for the modeling (10.2%) is the weighted average cost of capital (WACC) used in the National Renewable Energy Laboratory's 2016 Annual Technology Baseline (ATB). In the updated 2017 ATB, the same WACC is used to represent long-term average market conditions, while current market conditions are represented by a 8.2% WACC in accordance with the Energy Information Administrations's 2017 Annual Energy Outlook.

It is noted that some industry participants use discount rates as low as 6%. Federally-funded projects also use low discount rates, often around 3%. Using a lower discount rate would result in more projects being economical. Thus, the results presented in this analysis could be argued to represent a conservative view of solar and storage technology economics.

Citations

PV Cost Assumptions are based on NREL's 2016 "Annual Technology Baseline (ATB)". Golden, CO: National Renewable Energy Laboratory.
http://www.nrel.gov/analysis/data_tech_baseline.html

Storage cost assumptions are based on cost data collected by NREL, summarized in "Battery Energy Storage Market: Commercial Scale, Lithium-ion Projects in the U.S." by Joyce McLaren, Pieter Gagnon, Kate Anderson, Emma Elgqvist, Ran Fu, Tim Remo, October 2016.
http://www.nrel.gov/docs/fy17osti/67235.pdf

Utility Rate Database
http://en.openei.org/wiki/Utility_Rate_Database

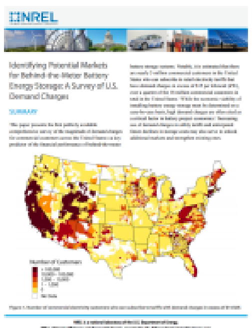
Renewable Energy Optimization Model
https://reopt.nrel.gov/

United States Climate Zones
http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/4_3a_ba_innov_buildingsciencecli-matemaps_011713.pdf

Load profiles are based on the Department of Energy Commercial Reference Buildings
https://energy.gov/eere/buildings/commercial-reference-buildings and created using Energy Plus Software
https://www.energyplus.net/

Related Work

McLaren, Joyce, and Seth Mullendore. 2018. ***Valuing the Resilience Provided by Solar and Battery Energy Storage Systems.*** Golden, CO: National Renewable Energy Laboratory. *https://www.nrel.gov/docs/fy18osti/70679.pdf.*



McLaren, Joyce, and Seth Mullendore. 2017. ***Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges.*** NREL/BR-6A20-68963. Golden, CO:National Renewable Energy Laboratory. *https://www.nrel.gov/docs/fy17osti/68963.pdf.*

Whitepaper:	https://www.nrel.gov/docs/fy17osti/68963.pdf
Data:	https://data.nrel.gov/submissions/74
Webinar:	https://www.cleanegroup.org/webinar/nrel-demand-charges-storage-market/

McLaren, Joyce, Pieter Gagnon, Kate Anderson, Emma Elgqvist, Ran Fu, and Tim Remo. 2016 ***Battery Energy Storage Market: Commercial Scale, Lithium-ion Projects in the U.S.*** NREL/PR-6A20-67235. Golden, CO: National Renewable Energy Laboratory. *https://www.nrel.gov/docs/fy17osti/67235.pdf.*

Simpkins, Travis, Kate Anderson, Dylan Cutler, and Dan Olis. 2016. ***Optimal Sizing of a Solar-Plus-Storage System for Utility Bill Savings and Resiliency Benefits.*** NREL/CP-7A40-66088 Golden, CO:National Renewable Energy Laboratory. *https://www.nrel.gov/docs/fy17osti/66088.pdf.*