Distribution Grid Impacts of Community Solar

Miguel Heleno, Juan Pablo Carvallo, Alan Valenzuela,
Greg Leventis, Cesca Miller and Jeff Deason

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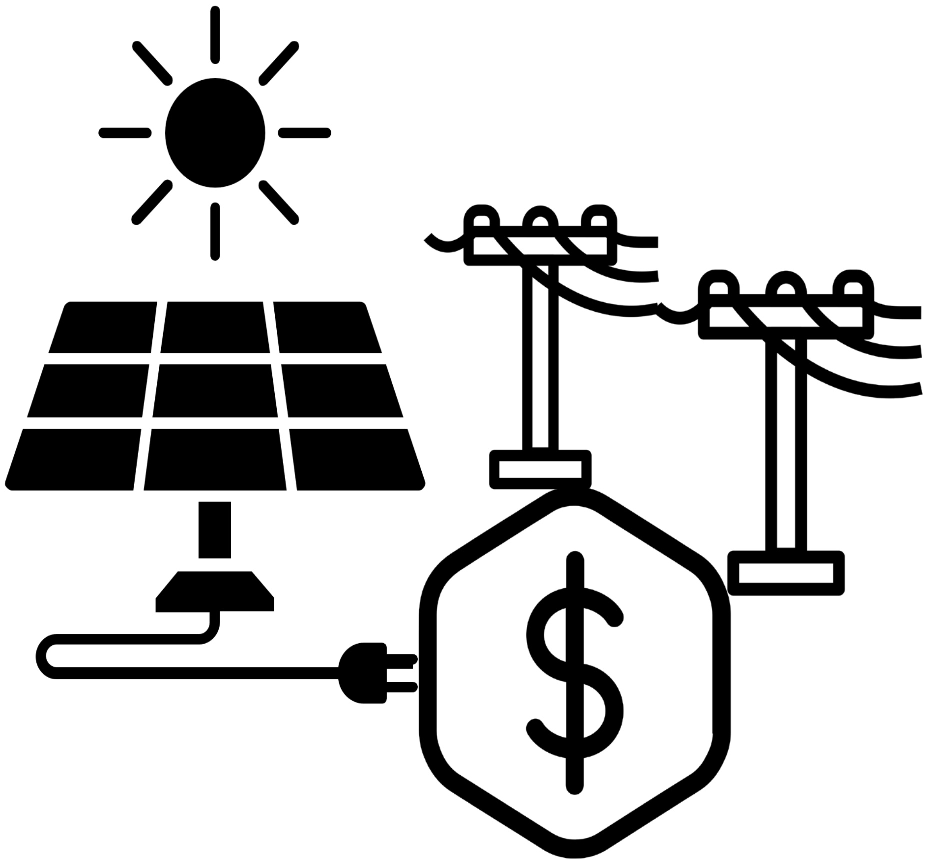
Introduction

Project Motivation

Community solar (CS) projects often face uncertain interconnection costs and fees associated with **distribution grid infrastructure upgrades** required to connect the project.

These costs can determine the economic viability of a CS project, but they are difficult to assess. Cost uncertainty can **discourage new projects** and prevent communities from accessing the benefits of community solar projects. At the same time, CS **deployment strategies** hold potential to **defer or avoid** some distribution costs due to new loads.



Community solar in a nutshell

- Community solar (CS) is defined as **"any solar project or purchasing program, within a geographic area**, in which the benefits of a solar project flow to multiple customers such as individuals, businesses, nonprofits, and other groups." (DOE, 2023)
- CS **subscribers** receive a fraction of the project capacity and the corresponding set bill credits for the electricity produced by the project. These credits may partially offset their electricity bills.
- CS **developers** typically size their projects as large as allowed by law or regulation (typically 1 to 5 MW) to gain economies of scale. Each jurisdiction has different rules to compensate for unsubscribed output, which means that some developers face more pressure than others to fully subscribe their projects.

CS challenges and opportunities

Challenges

To mitigate CS interconnection costs, it is important to:

i) find **least-cost** combinations of distribution system infrastructure **solutions** (transformer upgrades, reconductoring, voltage regulators, storage), and

ii) Understand how **location of CS projects** within a feeder impact distribution grid upgrade costs.

Opportunities

In certain situations, strategic siting of CS projects could **defer or avoid** distribution upgrades on feeders that are stressed due to new loads, such as those introduced by **beneficial electrification** or new lump loads (e.g., large data center).

Capturing this deferral value may reduce some utility infrastructure upgrade needs and keep down electricity rates for all customers.

Objectives and research questions

This study aims to **quantify CS impacts** on the distribution grid and provide **policy and regulatory insights** and CS **deployment strategies** to address them.

In particular, this study aims to answer the following research questions:

- How often do our modeled CS projects require distribution grid upgrades?
- What types of distribution grid upgrades are required by our modeled CS projects?
- What is the range of costs of these upgrades?
- Can CS provide cost deferral benefits for distribution systems? In what circumstances?
- To what extent can strategic siting of CS projects help alleviate costs and increase deferral benefits?

Technical distribution grid challenges

Quantifying distribution grid upgrades

Requires complex techno-economic models to find a **least-cost combination of grid upgrades** that ensure **safe operation** of the distribution system.

Given this complexity, it is hard to determine **cost causalities**.

There is **no established universal methodology** to determine the most economical distribution grid investment plan.

CS vs behind the meter (BtM) Solar

Unlike BtM solar, CS developers have an incentive to **maximize the project size**, resulting in high solar capacities connected to a **single point** of the network. CS grid impacts are therefore potentially more significant than BtM solar. However, the interconnection point for CS is not linked to a specific meter, making **CS siting more flexible** and offering the opportunity to mitigate impacts through siting.

Value of this research

- This is the first analysis that has systematically studied the technical impacts of CS projects on a wide range of distribution feeders using state-of-the-art optimization and power flow tools.
- The analysis employs Berkeley Lab's novel Least-cost Optimal Distribution Grid Expansion (LODGE) model, a deterministic version of the REPAIR model, that optimally upgrades hundreds or even thousands of distribution circuits or feeders. This is the first application of the LODGE model.
- LODGE finds the *least-cost portfolio* of traditional distribution system upgrades to integrate CS in combination with alternative solutions, such as utility-owned storage and downsizing CS capacity.
- Working with a set of least-cost solutions per feeder allows us to benchmark, compare and find techno-economic trends in CS interconnection.

Research approach and validation strategy

- This project is a modeling exercise. The Methodology section details our modeling approach. All reported costs and other results are modeled results, not results from actual upgrades.
  - Data from actual upgrades are scarce and not sufficient to explore forward-looking scenarios and alternatives to current utility planning practices.
  - To validate the methodology, we benchmark our modeled costs against empirical costs, which shows that our modeled costs are in the same range
- This project goes beyond a hosting capacity analysis.
  - Hosting capacity calculates the amount of solar that can be interconnected without adversely impacting power quality or reliability under existing control and protection systems and without infrastructure upgrades.
  - Our analysis considers whether CS projects would require upgrades to the distribution system and how much those upgrades would cost.

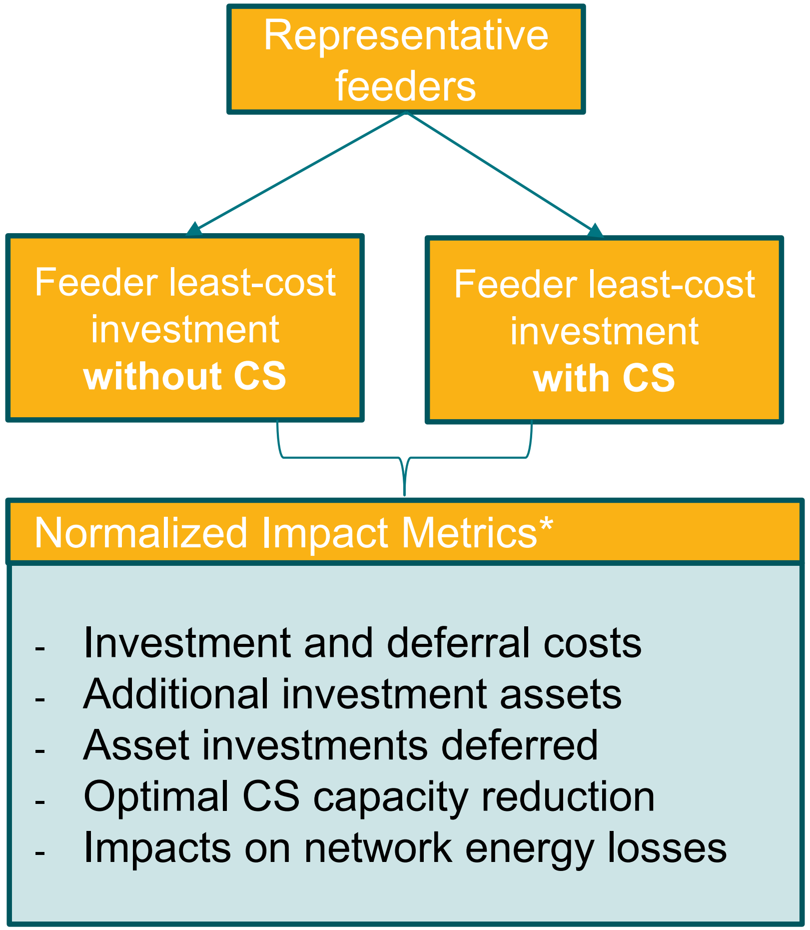
Aspects not included in this study

- Our analysis considers only distribution system upgrade costs. We do not weigh those costs against other CS project costs, such as land acquisition costs.
- We present distribution upgrade costs relative to feeder loads and CS project capacity. We do not evaluate stakeholder responsibilities regarding those costs.
- Distribution upgrade costs include major infrastructural upgrades required to ensure safe steady conditions of the grid. We do not consider costs such as:
  - Control, telemetry and Direct Transfer Trip (DTT) costs often required by utilities for interconnecting distributed generation;
  - Grid costs related to the upgrade of protection systems and voltage stability controls;
  - Upgrade costs related to equipment lifetime;
  - Transmission-related costs or other substation upgrades besides the transformer;
  - Utility revenue losses.

Methodology

Methodology: overview

- The study simulates a large set of feeders that can represent US distribution networks.
- For each representative feeder, it calculates the least-cost optimal investments needed to ensure the feeder’s safe operation in two situations: **i) without and ii) with** the presence of CS.
- It then calculates the CS interconnection costs by taking the **difference between** the least- cost investments **with and without CS**.



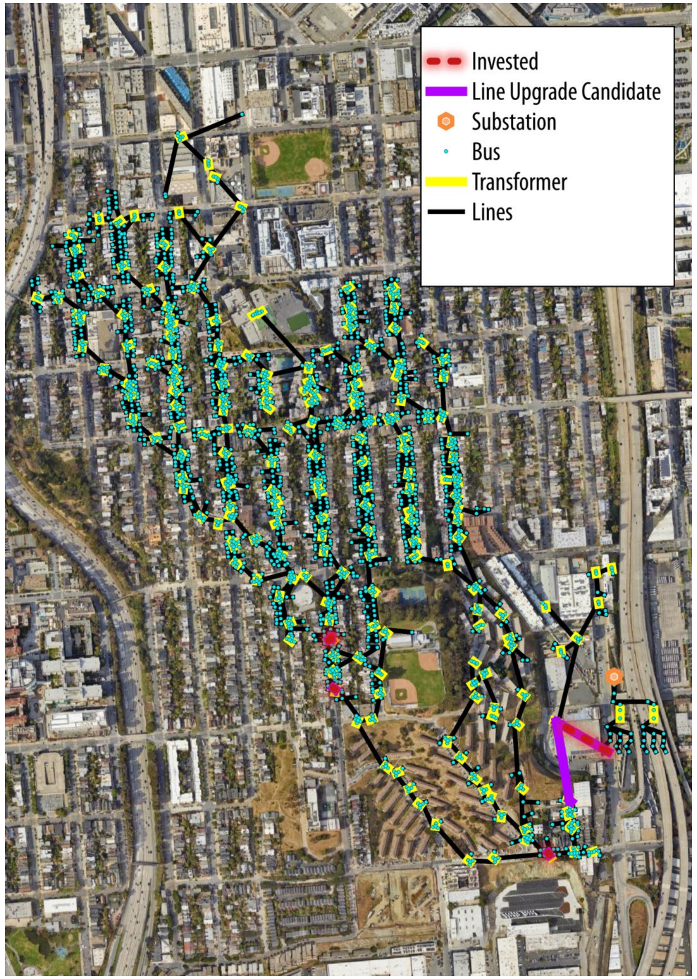
** To allow comparison of feeders with different sizes, impact results can be normalized per energy consumed on the feeder (MWh), per peak load (MW) or per CS capacity (MW).*

Methodology: netload scenarios

We model 3 scenarios on each feeder.

- **Base:** Feeder with netload scenario equal to the existing conditions of the feeder (included in Smart-DS–see next section).
- **High Rooftop PV*:** Starting from the "Base" scenario, we iteratively increase the pre-existing rooftop PV on the feeder until overvoltage or line capacity violations start to occur.
- **High Load**:** Starting from the "Base" scenario, we iteratively increase the load on the feeder until undervoltage or line capacity violations start to occur.

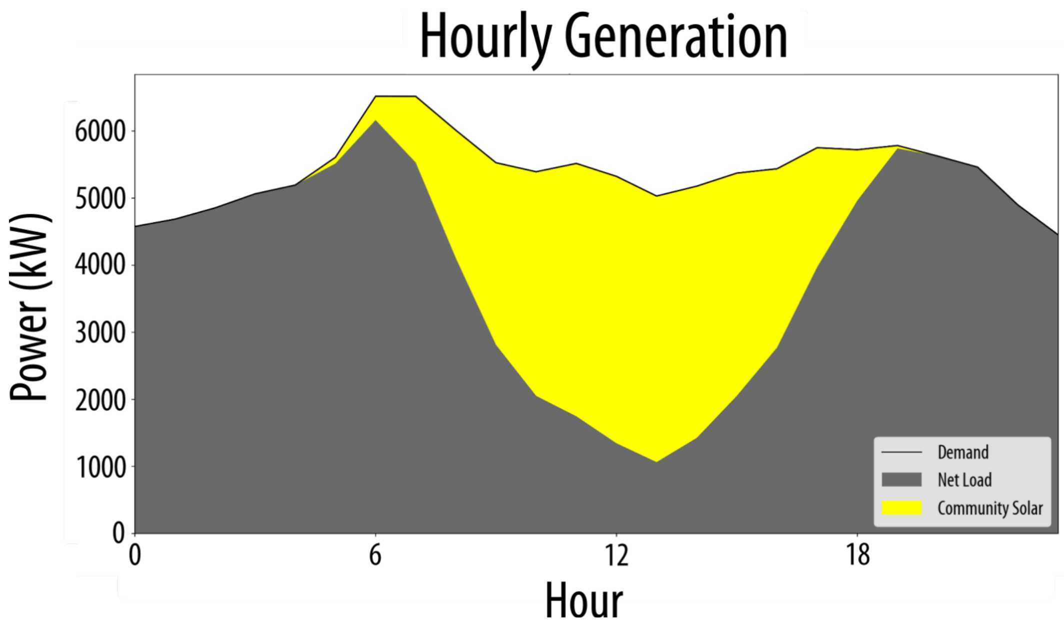
** The High Rooftop PV scenario represents a system where the adoption of rooftop PV puts the feeder near its hosting capacity, i.e., the amount of solar that can be interconnected without adversely impacting power quality.*
*** The High Load scenario represents a system that gets overloaded due to load growth — for example, driven by beneficial electrification of buildings and transportation sectors.*



Example of a "high load" scenario in an urban feeder. This scenario requires 5 potential line investments.

Methodology: community solar sizing

For all feeders analyzed, we sized the CS project's nameplate MW capacity equal to the minimum daily load (MDL) on the feeder. This sizing criterion is also widely used by CS project developers to maximize CS capacity.



Example of an hourly netload, considering a 4 MW CS project, sized following the minimum daily load (~4 MW at 12 AM)

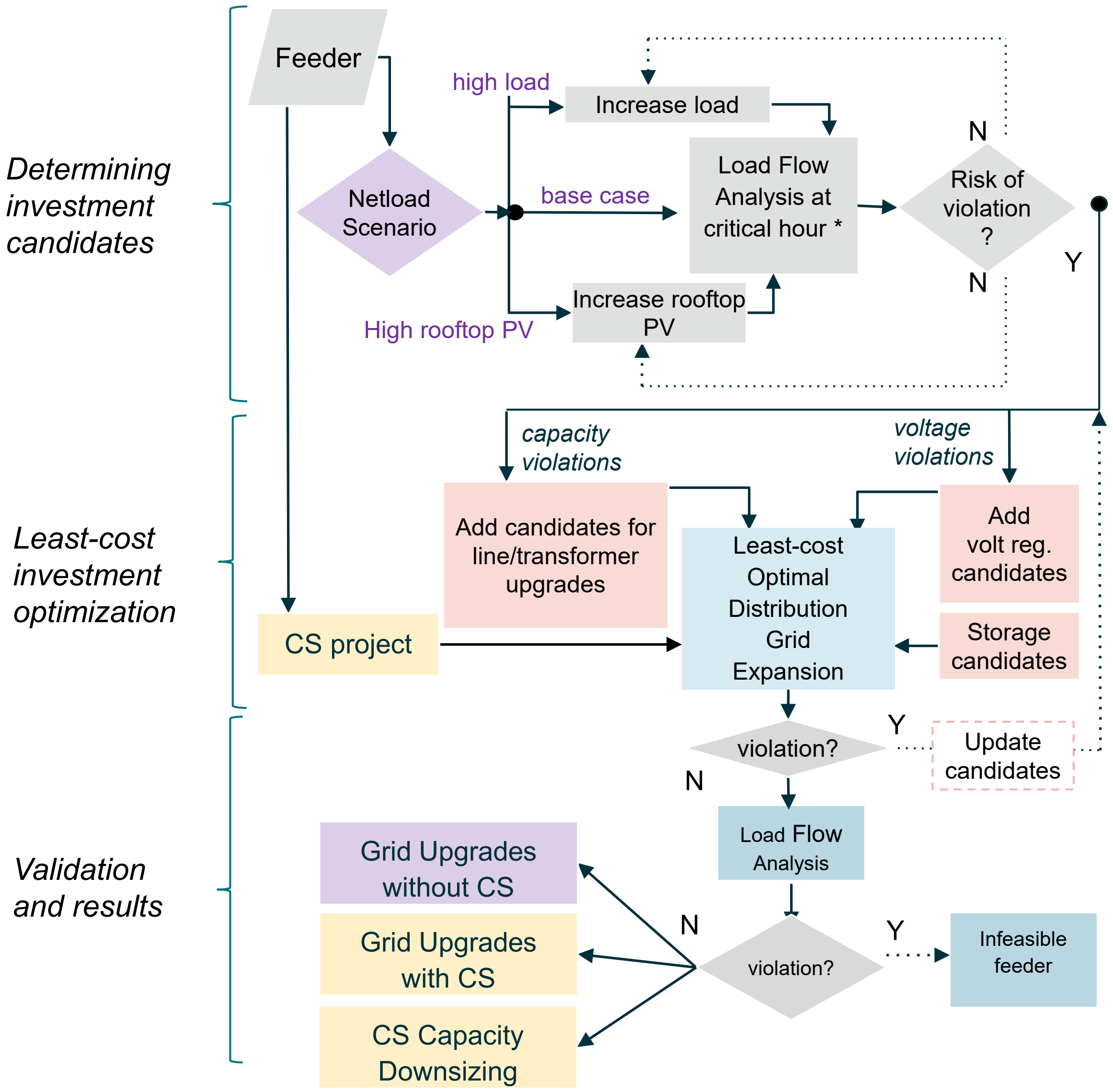
Sizing the CS project as a function of the feeder load allows us to evaluate the impact of CS projects for feeders of all sizes and compare results across feeders.

Methodology: grid upgrades

- For each netload scenario, a load flow analysis helps select potential distribution grid upgrade candidates.
- Our LODGE model calculates least cost feeder upgrade solutions.
- The CS interconnection cost is the difference between the feeder upgrade costs with and without CS.

Distribution Grid Upgrade Candidates	• OH/UG* line reconductoring • Transformers upgrade • Voltage regulators • Utility-owned storage

*Overhead/underground



Note: For “Base” and “High Load” scenarios, the algorithm performs a load flow at the peak hour, checking undervoltage violations. In “High Rooftop PV” scenario, load flow is at the netload valley, and the algorithm checks for overvoltage violations.

Data

Feeders, Netload Scenarios and Costs

Feeders: SMART-DS dataset

- The feeders are synthetic realistic distribution systems from NREL's SMART-DS dataset that have been validated against real utility data.
- The dataset includes annual netload scenarios, with hourly demand and PV profiles for each node of the network.
- This study simulated more than 2,500 feeders, 95-98% of the entire SMART-DS set. It is the most comprehensive CS distribution impact analysis in the literature.

	Netload Scenarios		
	Base	**Load**	**PV**
Feeders in SMART-DS	2,711	2,711	2,711
Feeders included in the analysis	2,646	2,566	2,654
% feeders considered	**98%**	**95%**	**98%**

A small fraction of the SMART-DS feeders were not included in the analysis, because either an initial power flow did not converge, or no solution existed for the Least Cost Optimal Distribution Grid Expansion model.

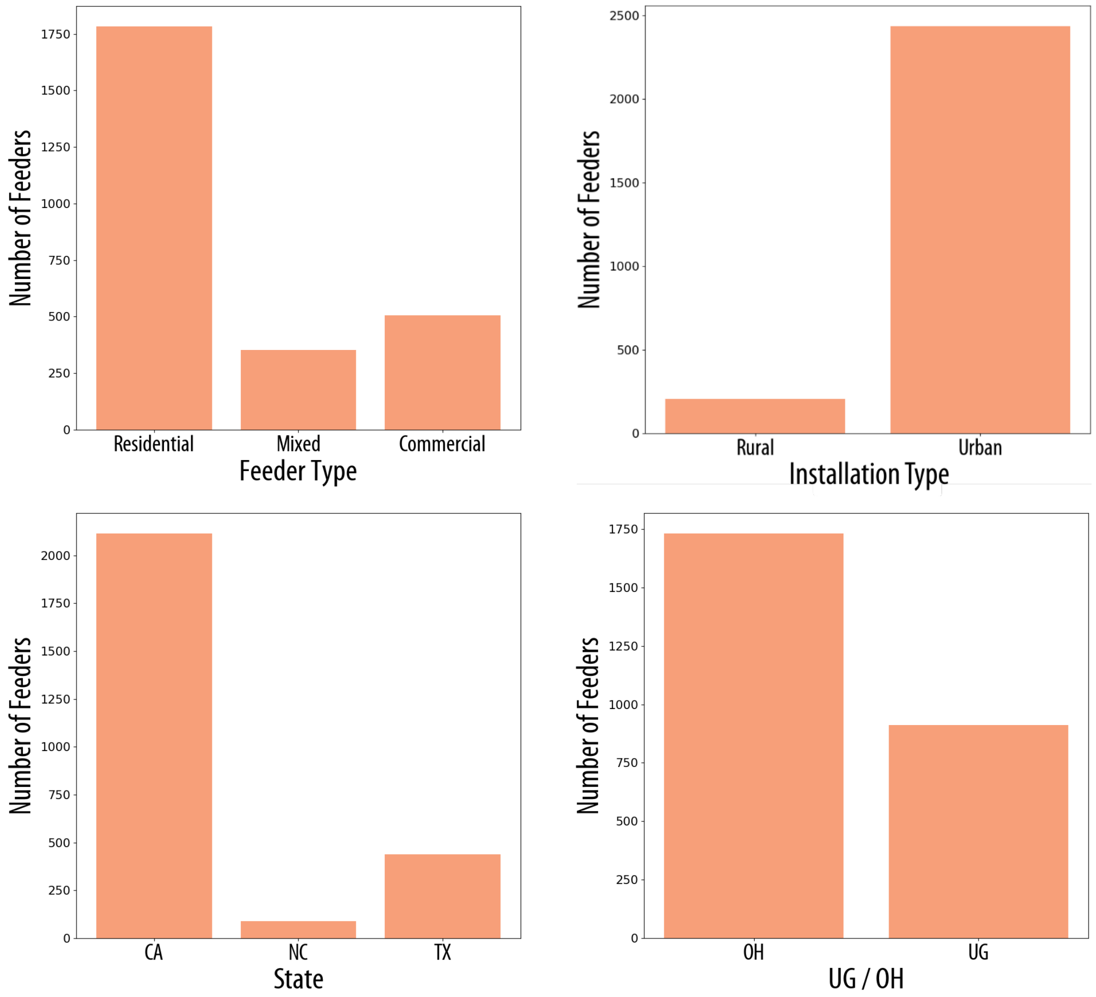
Region	Subregion	Total Peak Load (MW)	Total Number of Customers
AUS	**6**	3,099	307,236
GSO	**3**	808	70,551
SFO	**35**	13,588	2,265,554

Load and number of consumers across the 3 SMART-DS regions considered in this study: Austin TX (AUS), Greensboro, NC (GSO) and San Francisco Bay Area (SFO).

Example of SMART-DS subregions in San Francisco.

Feeder characteristics

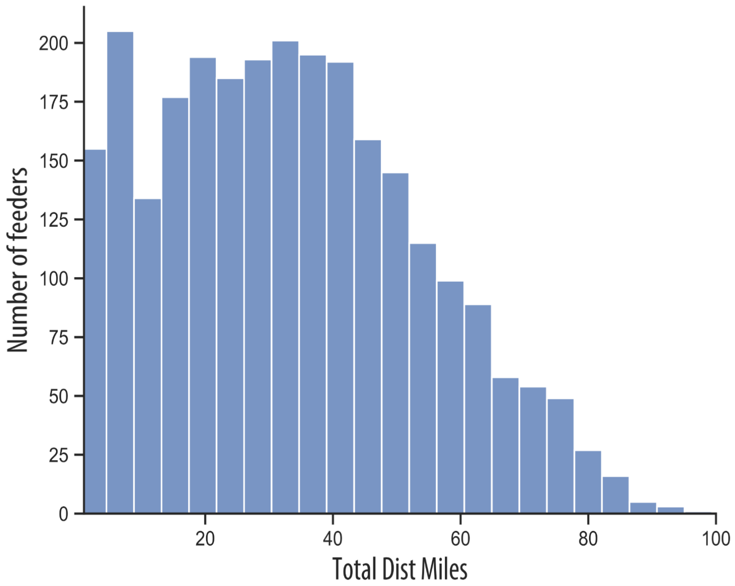
- The set of feeders included in the analysis covers different geographies (rural/urban in 3 states), feeder installation types, lines (overhead (OH)/underground (UG)), and customer classes (residential/ commercial/mixed).
- Feeders are classified as *Commercial* if the share of commercial consumers is more than 50%, *Residential* if the share of commercial consumers is less than 20% and *Mixed* otherwise.

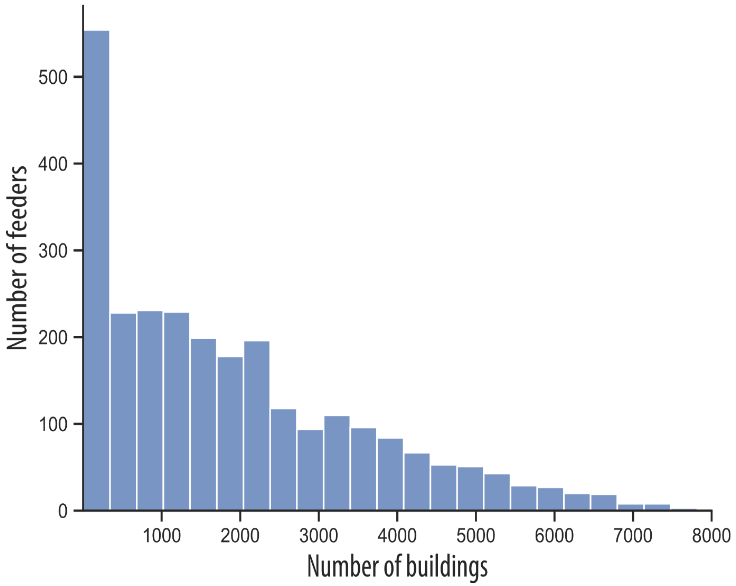


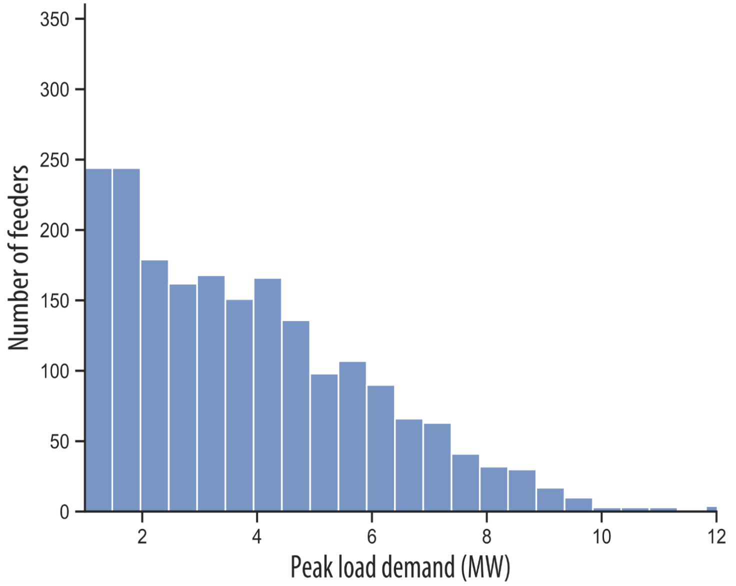
Distribution of the feeders considered in the analysis across different types, geographies and installation.

Feeder sizes

The modeled feeders include a wide range of feeder lengths, MW of peak load demand and number of consumers. Feeders range from dozens to thousands of consumers.







Cost data: infrastructure upgrade

Voltage Regulators

	California Costs ($)	Non-CA Costs ($)
Voltage Regulator	221,763	38,569

Voltage regulator costs were calculated based on NREL's distribution system upgrade costs DB. Given the difference between CA and non-CA costs in the DB, costs were separated by location. Lifetime of new regulator assets was assumed to be 25 years.

Transformer Upgrade

	Cost ($ thousand)	Capacity (MVA)	Lifetime (yr)
Transformer A	250	11	30
Transformer B	600	15	30
Transformer C	947	20	30
Transformer D	1400	35	30
Transformer E	1900	40	30
Transformer F	5000	100	30
Transformer G	11000	500	30

Transformer upgrades were calculated based on the $/KVA values reported on NREL's distribution system upgrade costs DB. The range of transformer sizes matches the different system sizes in Smart-DS. Lifetime of new transformer assets was assumed to be 30 years.

Energy Storage

	Costs ($/kW)
2-hour Battery	634

Battery costs were calculated based on NREL's distribution system upgrade costs DB. Costs include inverter. Assumed battery lifetime was 15 years.

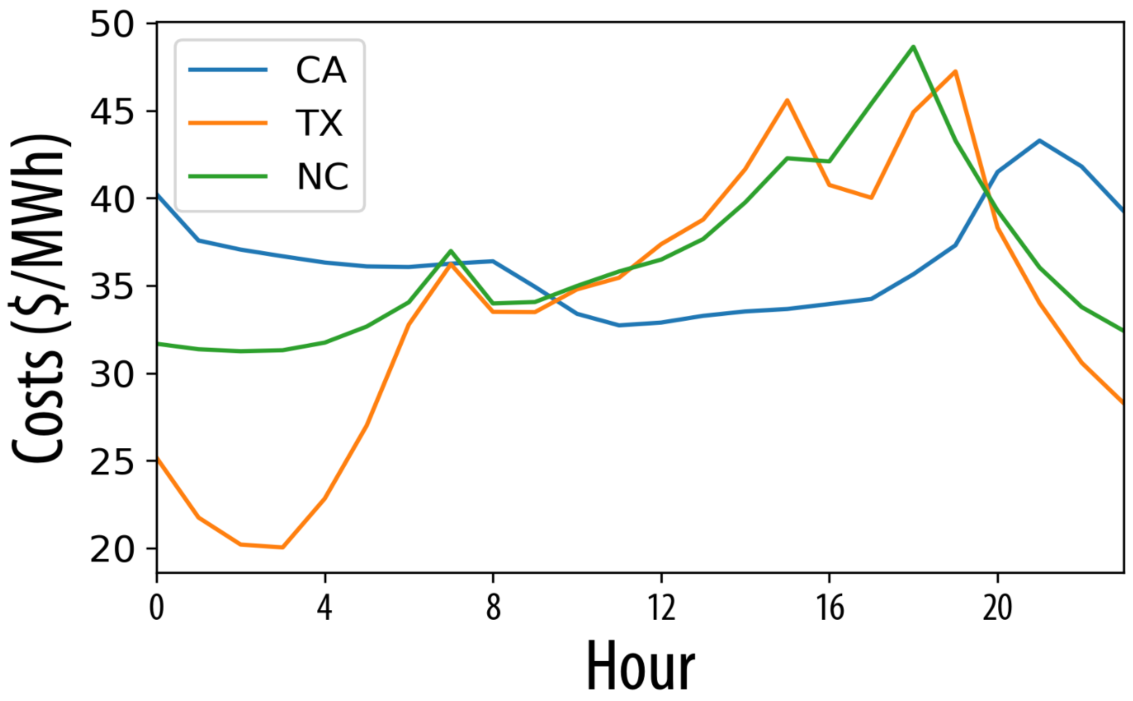
Reconductoring

Conductor Type and Gauge	California (k$/mile)			Non-California (k$/mile)		
	Rural OH	Urban OH	Urban UG	Rural OH	Urban OH	Urban UG
ACSR #4	892	1,510	1,167	644	1,088	174
ACSR #2	1,133	1,918	1,482	818	1,381	221
ACSR 1/0	1,704	2,884	2,229	1,230	2,077	333
ACSR 3/0	2,597	4,394	3,396	1,875	3,165	507
ACSR 4/0	3,248	5,497	4,247	2,345	3,959	634
ACSR 336.4	5,033	8,517	6,581	3,633	6,135	983
ACSR 477	6,978	11,809	9,125	5,037	8,506	1,363

Reconductoring costs were calculated based on NREL's distribution system upgrade costs DB. Given the difference between CA and non-CA costs in the DB, costs were separated by location. Lifetime of new conductor assets was assumed to be 30 years.

Energy prices

- Average hourly prices were considered for different states.
- These prices represent the hourly cost of electricity at the substation.
- Prices are used in this analysis to **value the cost of PV curtailment**, when LODGE selects PV curtailment as a cost mitigation strategy (discussed in the next section).



Average hourly wholesale prices in the day, calculated from the 8,760 values of LMPs in the Cambium dataset.

Impact Analysis

How do CS projects impact distribution feeder costs in different contexts?
What do these impacts mean for the distribution grid and for CS projects?

Classifying CS interconnection costs

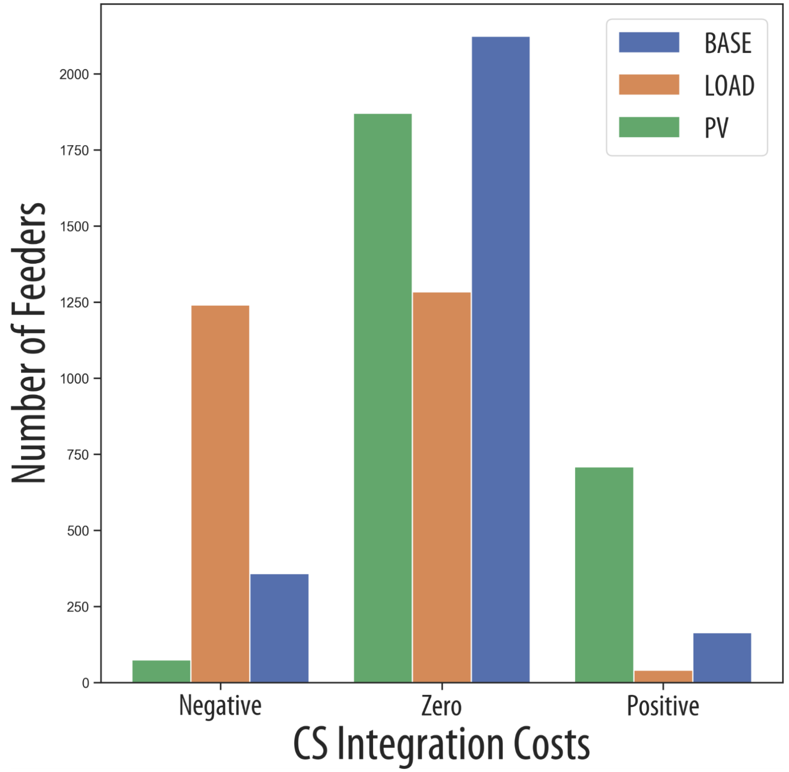
We cluster distribution upgrade costs due to CS interconnection* in three categories:

- **Negative:** This occurs when a feeder with an operating CS project has upgrade costs that are lower than a feeder with no CS project. In other words, the CS project is *deferring* (or avoiding) grid upgrades that would otherwise be needed.
- **Zero:** This occurs when feeders can host a CS project without incremental upgrades, in comparison with the same feeder without CS.
- **Positive:** This occurs when CS projects require grid upgrades whose cost is higher than the upgrades needed (if any) on the same feeder without the CS project.

**Note: as mentioned in the methodology section, modeled distribution upgrade costs include annualized investments (or deferrals) in feeder reconductoring, substation transformers, voltage regulators, and utility-owned storage.*

Overall CS impacts on distribution system costs

On most feeders in our study, under baseline conditions, CS projects do not require additional distribution grid infrastructure investments. This can be explained by the way we sized CS projects, with the embedded intention to minimize grid impacts.



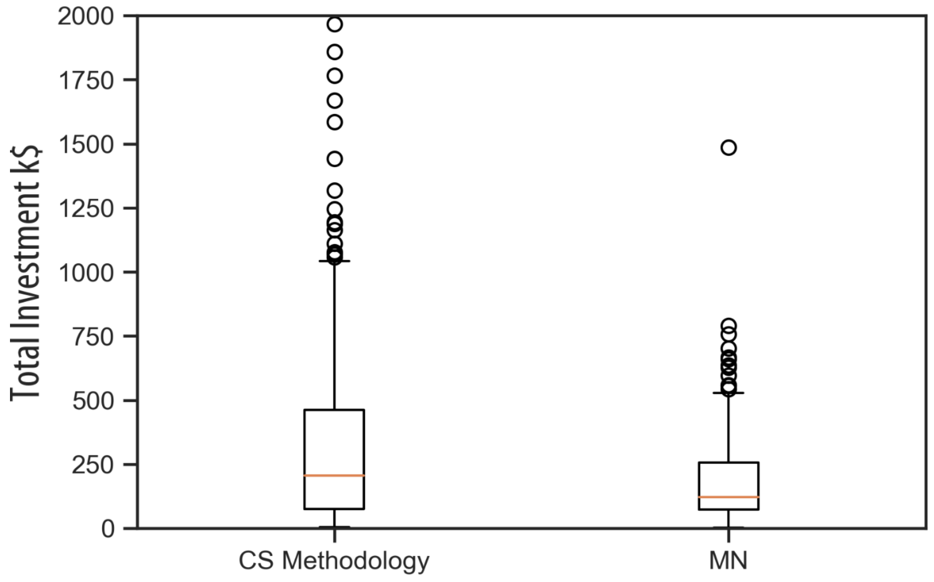
If these feeders become highly loaded, CS projects lead to *negative* distribution grid infrastructure costs (investment deferral) in approximately 50% of the cases.

If these feeders already have a high penetration of rooftop PV, CS projects require new grid investments in approximately 30% of the cases.

The large number of feeders with zero impact suggests that sizing guidelines based on the MDL may be too conservative and larger CS sizes may be possible.

Integration costs

When CS project interconnection costs are positive, average distribution feeder upgrade costs are $188k. However, in a small number of extreme cases, upgrade costs may reach $2M (e.g., when a substation transformer upgrade is needed).

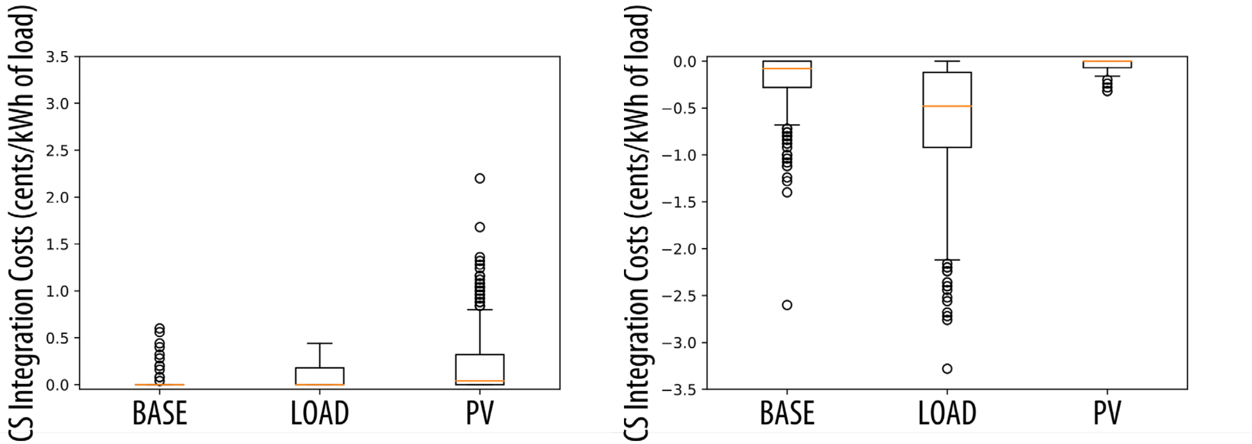


Left: Distribution of positive CS integration costs obtained in this study for the PV Scenario. Right: Distribution of 210 real CS integration costs reported by the Solar Gardens Program in MN.

Validating these estimates…

The **simulated cost of the 710** feeders in this study that require distribution infrastructure upgrades is very similar to the upgrade costs of **210 actual CS projects** for the Solar Gardens program in Minnesota, reported in 2020 and 2021. The similarity in the range of costs indicates that our methodology realistically captures the key drivers of CS integration costs.

Impact on distribution grid costs relative to feeder load



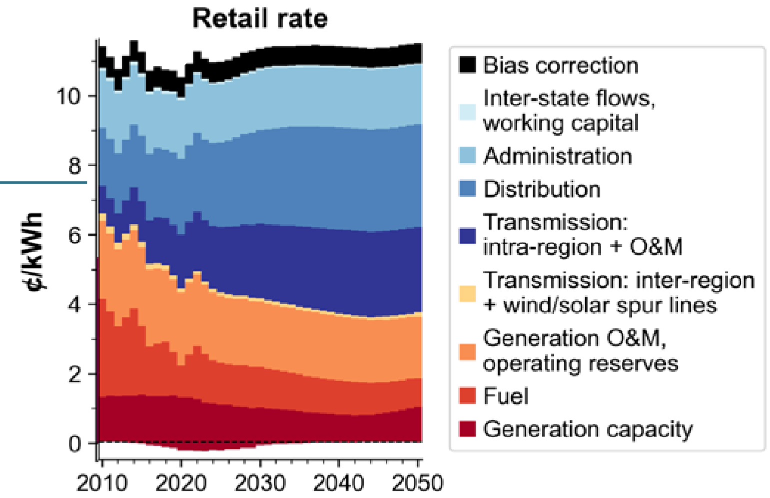
Distribution of positive (left) and negative (right) CS integration costs for the three scenarios considered in this analysis.

CS-related costs and deferral benefits are moderate for most feeders (~0.2 ₵/kWh). However, in extreme cases, they may exceed 2₵ per kWh of feeder load.

Distribution costs **~2₵/kWh**

Comparing with total distribution costs…

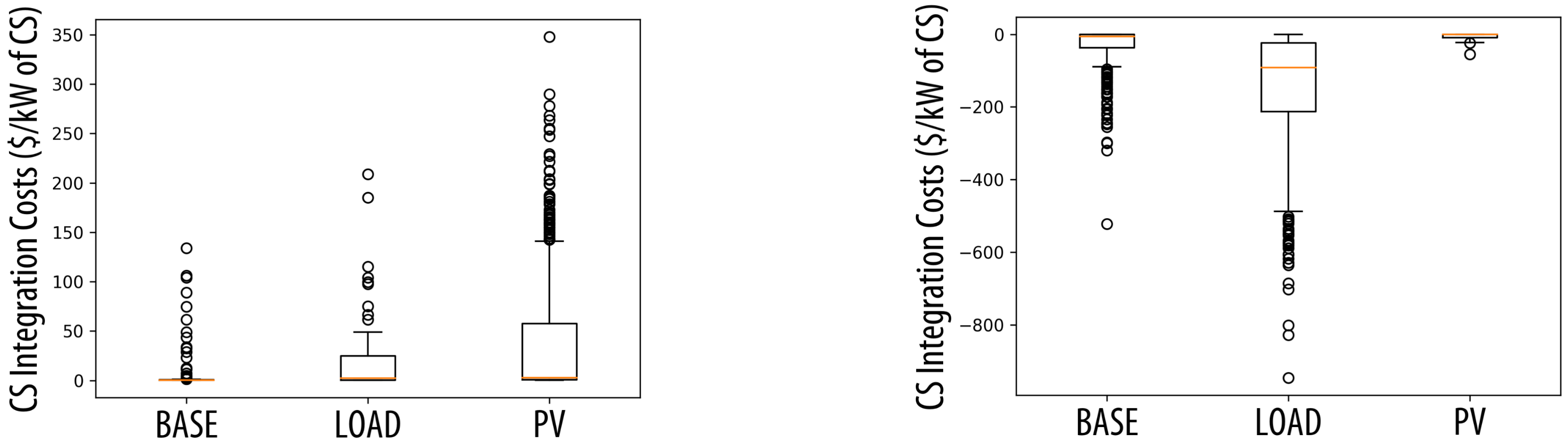
Assuming a ~2₵/kWh distribution cost, CS impacts represent less than 10% of this value in most cases. In extreme cases CS impacts can reach 100% of total distribution costs.



Disaggregated components of retail rates, from "Retail Rate Projections for Long-Term Electricity System Models" Report.

Impact per MW of CS installed

For most feeders, grid costs and benefits due to the presence of CS are less than $50/kW installed. For feeders near their hosting capacity limit, the costs can go beyond $250/kW of CS installed in some cases. On the other hand, in heavily loaded feeders the *benefits* can exceed $500/kW of CS installed in some cases.



Distribution of positive (left) and negative (right) CS integration costs for the three scenarios considered in this analysis. The figures show the overnight capital costs of the investments needed/deferred per MW of community solar installed.

Feeder Type Analysis

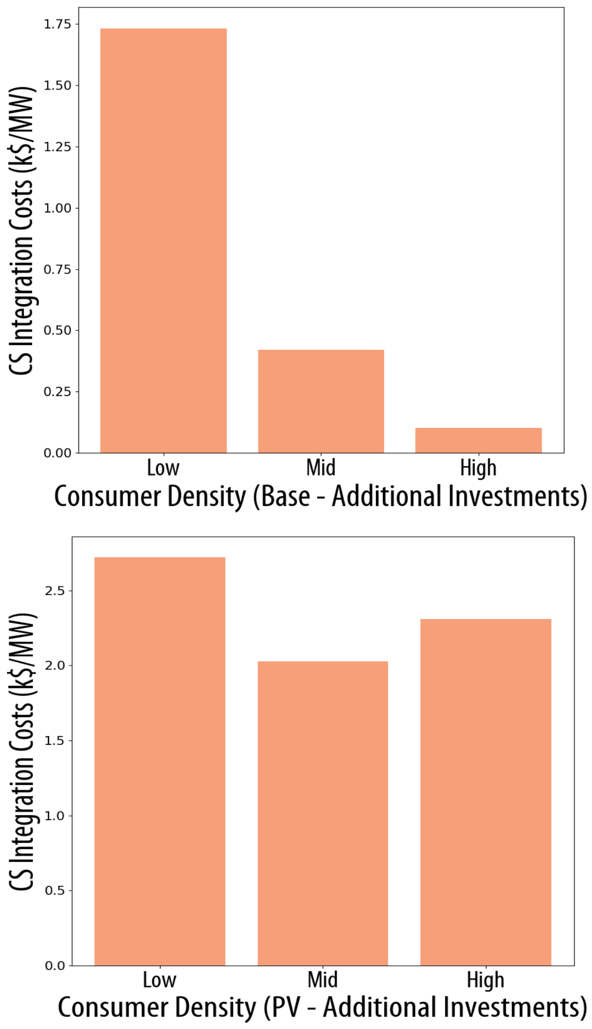
How do CS impacts differ across different feeder types?

Consumer density

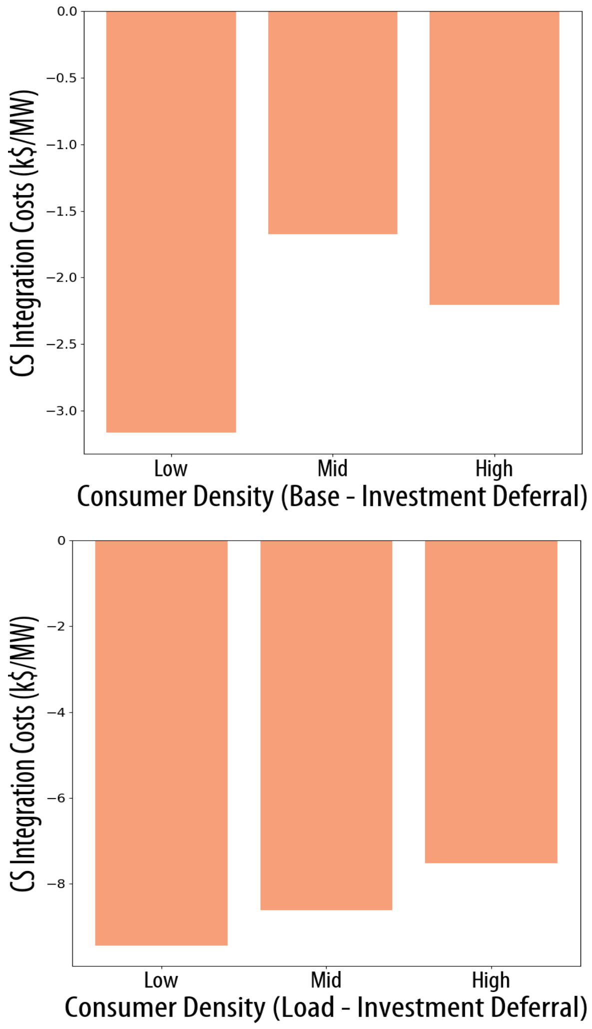
Community solar projects tend to require higher integration costs in **low-density feeders**, i.e., feeders with a low number of consumers per miles of line.

The average investment deferral benefits of CS projects are slightly higher in low-density feeders.

This suggests that CS projects located in dense urban feeders have lower interconnection costs. However, this density benefit may not be enough to compensate for other project costs (e.g., land) in urban areas.



Average positive CS Interconnection Cost per consumer density. Top: base scenario; bottom: High Rooftop PV scenario.

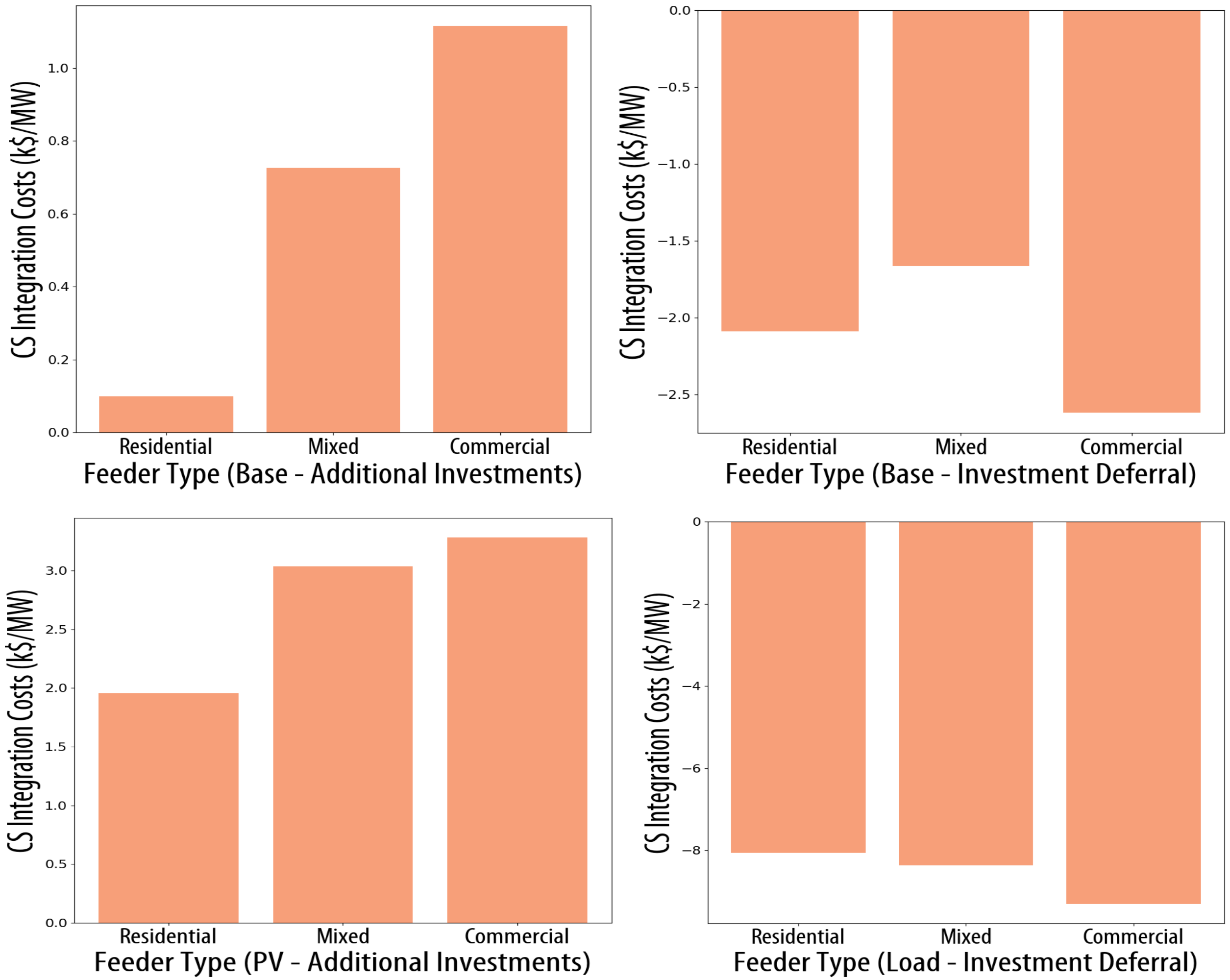


Average negative CS Interconnection Cost per consumer density. Top: base scenario; bottom: Load scenario.

Consumer type

CS projects tend to require higher interconnection costs for feeders serving **commercial consumers.**

Commercial feeders tend to have loads concentrated in fewer locations. A CS project on a commercial feeder may create a locational mismatch of netload, requiring higher distribution upgrade investments.



Average positive CS Integration Cost per consumer type. Top: base scenario; bottom: High Rooftop PV scenario

Average negative CS Integration Cost per consumer type. Top: base scenario; bottom: Load scenario.

CS Integration Solutions and Distribution Grid Impacts

What type of infrastructure upgrades does CS require?

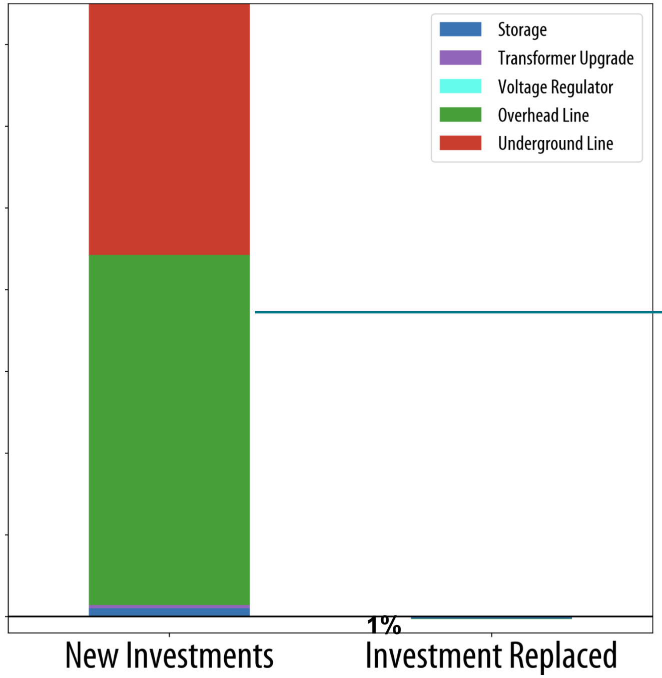
What type of infrastructure upgrades can CS help defer?

How often is reducing CS capacity part of a least cost solution?

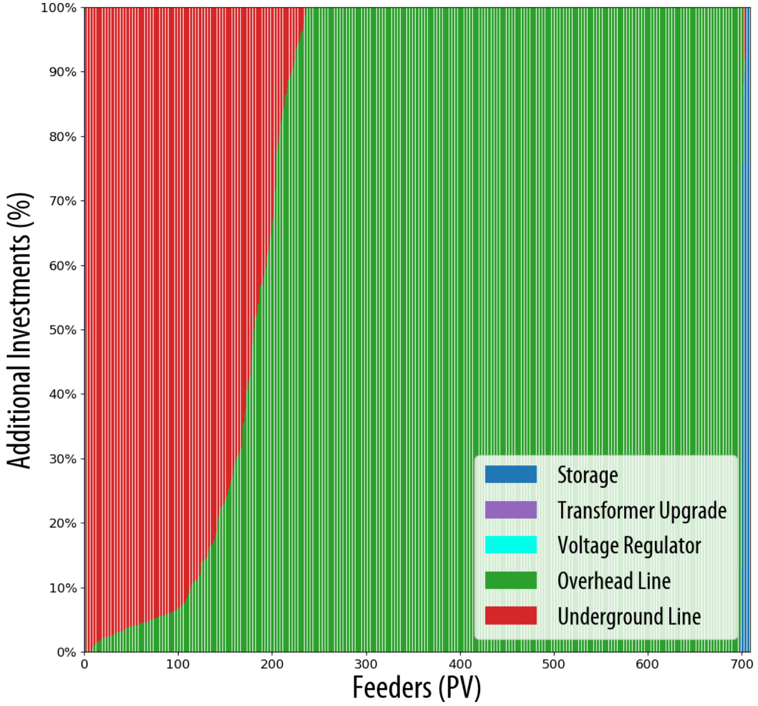
How does CS impact distribution grid losses?

Upgrades when integration costs are positive

When CS integration requires additional costs, those costs are almost exclusively for investments in **overhead and underground reconductoring**. Without CS, those feeders would be operating safely without any upgrades.



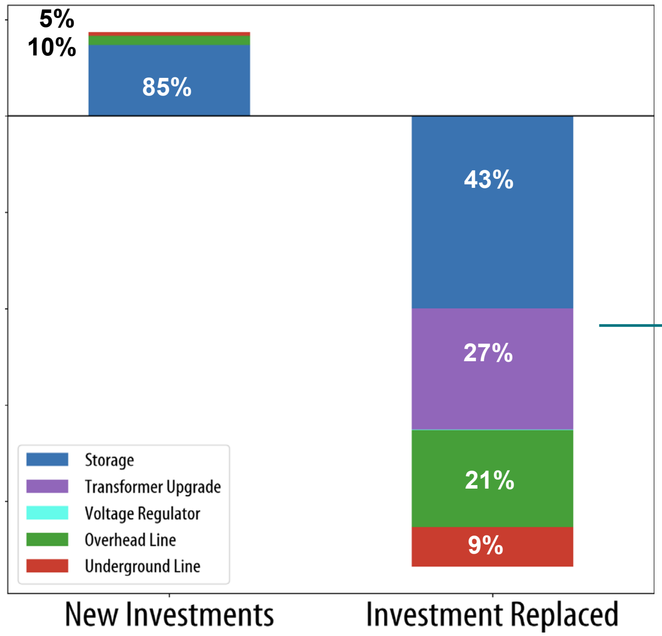
Cumulative changes in the distribution of grid upgrades when CS integration costs are positive [High Rooftop PV Case]. "New Investments" refer to the upgrades required to integrate CS that are not required for the original feeder. "Investments Replaced" refers to the upgrades required for the original feeder that are not required when CS is added.



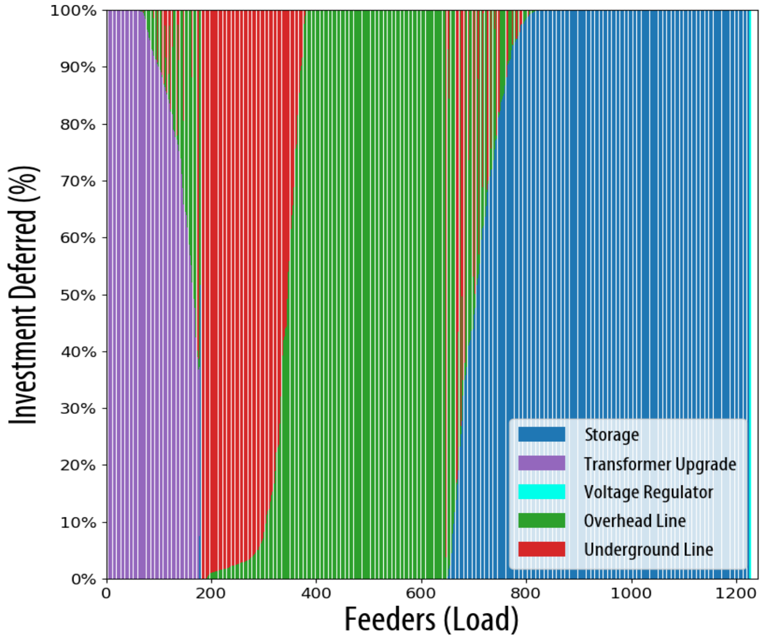
The distribution of new investments across the 700 feeders, in which CS presence resulted in costs. [High Rooftop PV Case]

Upgrades when integration costs are negative

Even when net costs are negative, **upgrades may still be required**. However, the net costs include **deferring significantly larger upgrades** (a mix of transformer, storage and reconductoring) that would be needed without the CS project.



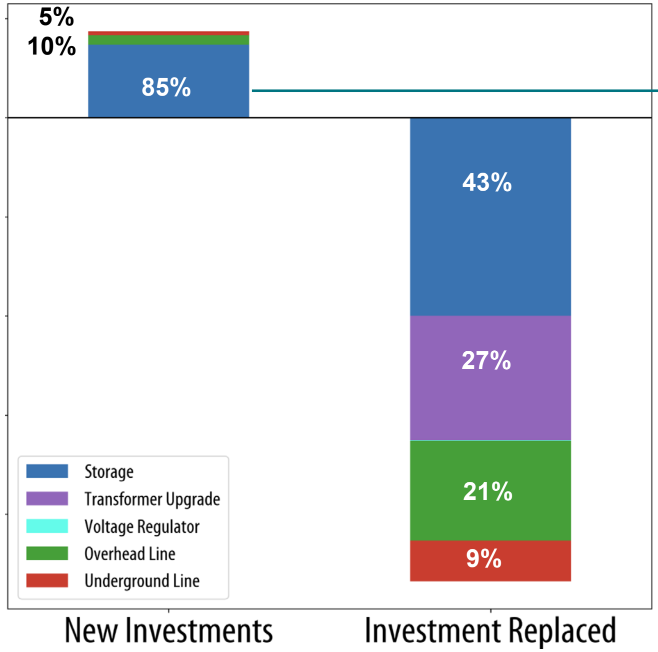
Cumulative changes in the distribution of grid upgrades when CS integration costs are negative [Load Case]. "New Investments" refer to the upgrades required to integrate CS that are not required for the original feeder. "Investments Replaced" refer to the upgrades required for the original feeder that are not required when CS is added.



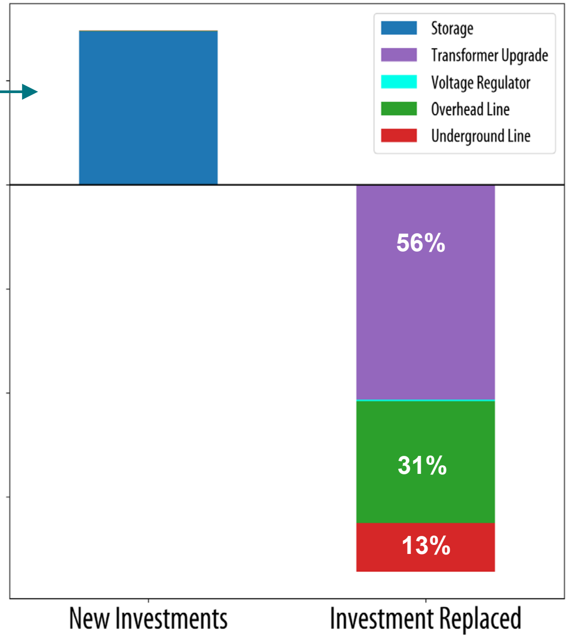
The distribution of investments deferred across the 1,200 feeders, in which CS presence resulted in negative costs [Load Case].

The role of storage in investment deferral

The LODGE model often selects utility-owned, front-of-the-meter storage as a new investment when the overall presence of CS leads to deferral. In these cases, storage functions as a non-wires alternative to defer reconductoring and transformer upgrades.



Cumulative changes in distribution of grid upgrades when CS integration costs are negative [Load Case]. "New Investments" refer to the upgrades required to integrate CS that are not required for the original feeder. "Investments Replaced" refer to the upgrades required for the original feeder that are not required when CS is added.



Cumulative changes in the distribution of grid upgrades when storage helps CS defer larger costs [Load Case]. "New Investments" refer to the upgrades required to integrate CS that are not required for the original feeder. "Investments Replaced" refer to the upgrades required for the original feeder that are not required when CS is added.

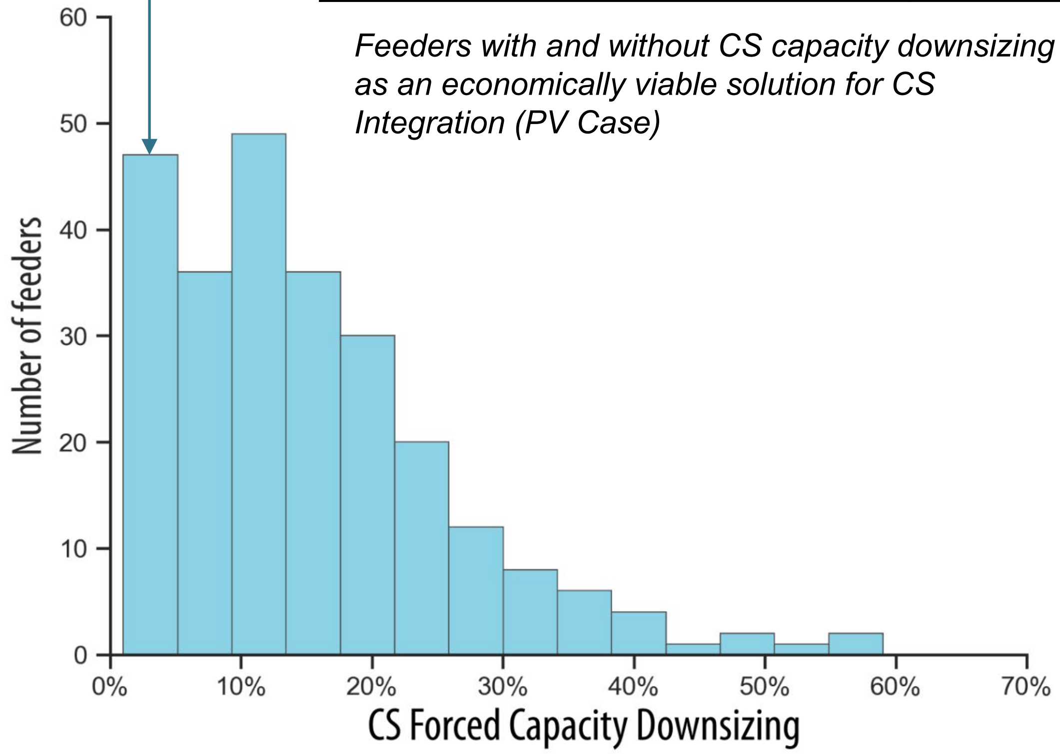
Community solar capacity downsizing

When grid infrastructure upgrades are not technically possible or economically viable for CS integration, the LODGE model selects **capacity downsizing** as a techno-economic solution to ensure the feasibility of distribution grid operation.

CS capacity downsizing in our model only occurs in a small number of cases (approx. 10%). In about 80% of these cases, reductions are less than 20% of the project's original target capacity.

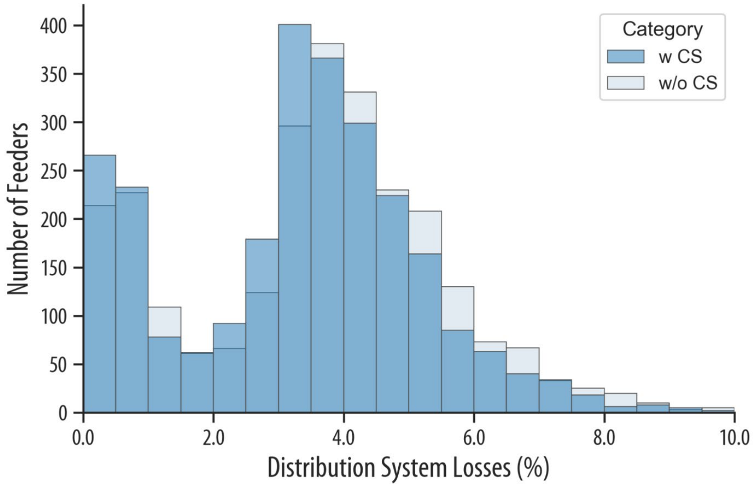
	# Feeders
Without Capacity Downsizing	2,268
With Capacity Downsizing	359

Feeders with and without CS capacity downsizing as an economically viable solution for CS Integration (PV Case)

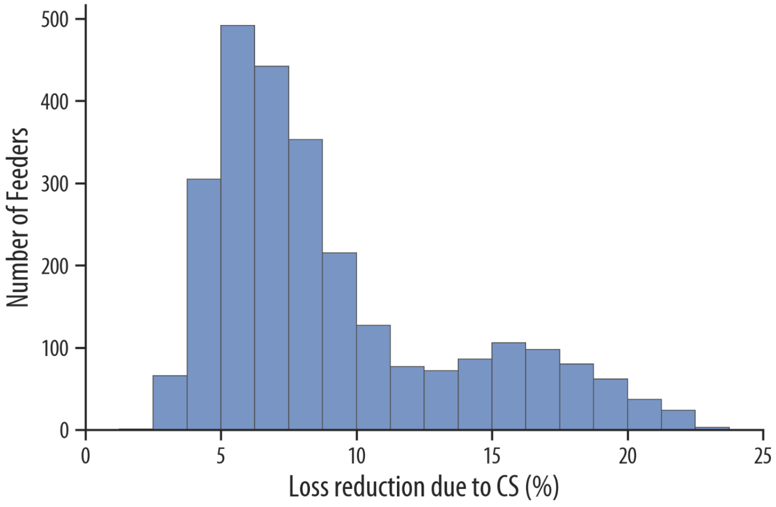


Distribution grid line loss reduction from CS

Besides impacts on distribution system investments, CS can bring grid operational benefits, namely reducing distribution line losses. The CS projects analyzed reduced line losses by between 10% and 20% for the primary distribution system.



Total distribution losses in the primary distribution network (medium-voltage) with and without CS on a typical day, as a percentage of the daily load [Base Case] - 2,646 feeders



Distribution losses reduction for the primary distribution network (medium-voltage) with and without CS on a typical day, as a percentage of the daily load [Base Case]

Strategic Siting

How can strategic siting help mitigate CS grid impacts?

Strategic siting potential

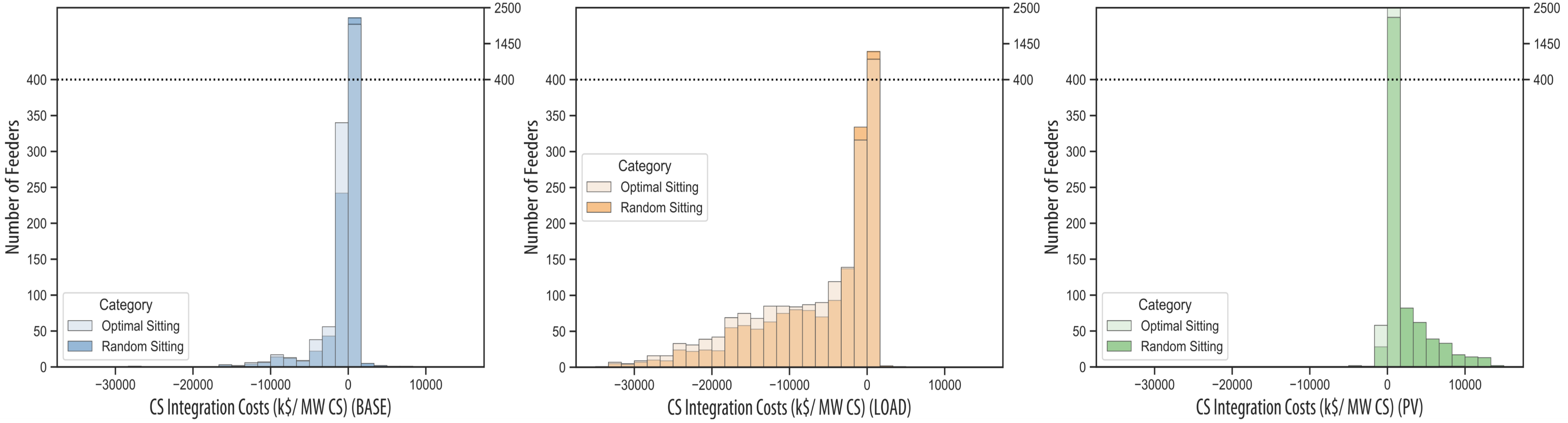
An important difference between CS and BtM PV (such as rooftop systems) is how each is sited. BtM PV is sited at a residence or business for individual utility customers. Conversely, CS developers and utilities can seek to incentivize siting CS at different (potentially strategic) locations on a feeder, provided a suitable site is available.

Our analysis shows that strategically siting these projects on the feeder can provide larger grid benefits, such as investment deferrals, as discussed on the next few slides. We model installation of CS in three locations on each feeder – at the top, middle, and bottom of the feeder – and compare the impacts. Depending on feeder characteristics, different CS locations on the feeder will optimize benefits.

Strategic siting – impacts on cost and deferral

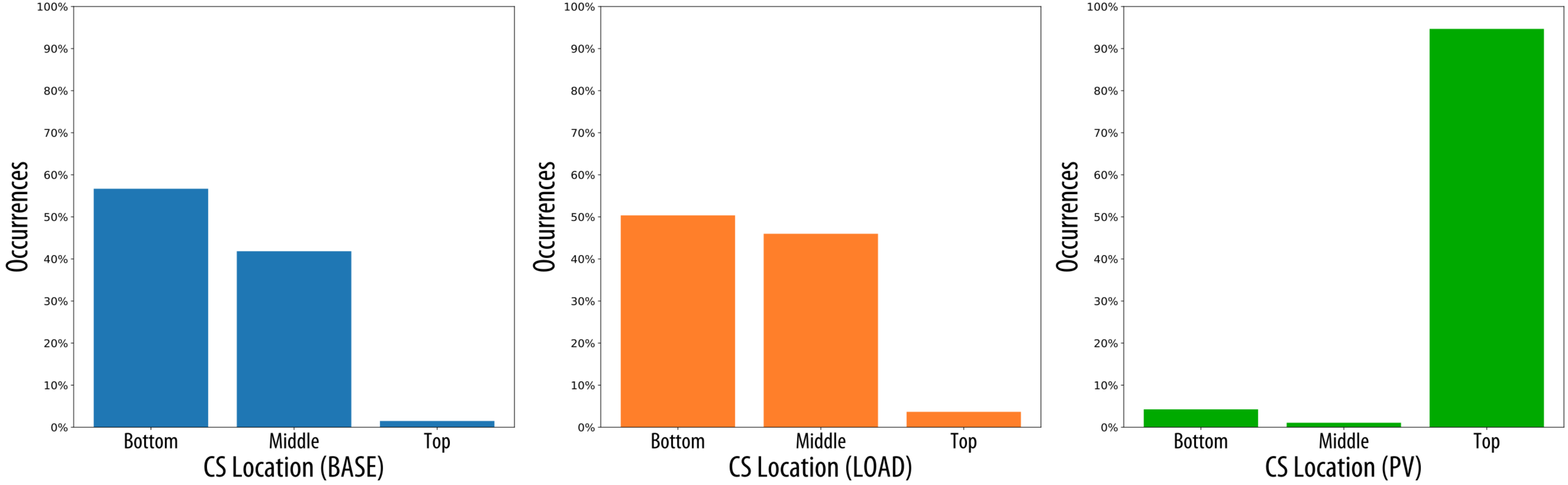
Strategic siting of CS can reduce upgrade costs and increase deferral value in all three scenarios studied. In particular, strategic siting can virtually eliminate the cases of very high interconnection costs on feeders near their hosting capacity.

These results strongly suggest that CS projects facing high integration costs should **explore alternate sites on the same feeder as a cost reduction strategy**.



Strategic siting - location comparisons

We explored the logic of strategic CS siting by looking at the project locations chosen by the model to minimize costs. When feeders are loaded, CS projects are generally located in the middle and at the bottom of the network to help serve load on the feeder down the line. For feeders with pre-existing rooftop PV, CS is better sited at the top of the feeders (i.e., closer to the substation), minimizing investments necessary to carry that load to other feeders.

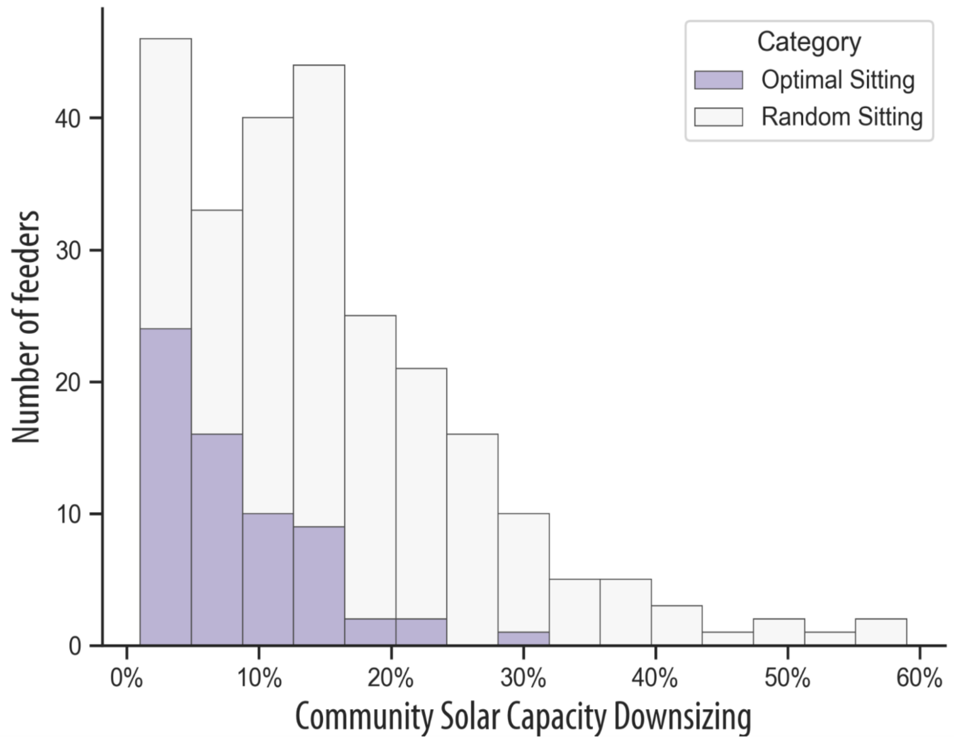


Strategic siting - need for CS downsizing

Strategic siting also reduces the need for CS capacity downsizing. With strategic siting, there are significantly fewer cases in our study in which downsizing is part of the least cost CS integration strategy.

	# Feeders
Capacity Downsizing – Random Siting	359
Capacity Downsizing – Optimal Siting	66

The number of feeders with CS capacity downsizing as an economically viable solution for CS Integration. Comparison between random and optimal siting (PV Case).



Summary and
Policy and Regulatory Insights

Takeaways: impact analysis

- Under current feeder conditions, most CS projects do not require any additional distribution grid infrastructure investments. Only 7% of the feeders we modeled required upgrades to support CS in the base case. Feeders that are already heavily loaded with distributed PV are more likely to require upgrades.
- CS is more likely to defer distribution system upgrades that would otherwise be required. Up to 15% of the modeled feeders benefit from deferred upgrades due to CS in the base case. In our high load scenarios, half of the modeled feeders benefit from deferred upgrades due to CS.
- When CS does require distribution system upgrades, they represent 10% of the average distribution cost embedded in typical electricity rates. From the perspective of a CS developer, these costs often represent less than $50/kW.
- Difference in interconnection costs by feeder density suggest that CS project interconnection costs are lower for urban and residential feeders.

Takeaways: CS integration solutions (1)

- Reconductoring is the most common distribution system upgrade required to accommodate CS at least cost.
- The most common distribution system deferrals enabled by CS are a mix of reconductoring, utility-owned storage and transformer upgrades.
- When a CS project results in net deferral benefits, it can still require some distribution system upgrades. This suggests that interconnection analyses that focus exclusively on grid upgrades and not on deferrals may overestimate CS interconnection costs. Utilities should conduct rigorous analysis of both costs and potential deferrals, with and without CS, to properly quantify CS distribution system cost impacts.
- Downsizing CS projects due to distribution system constraints is rarely necessary in our modeling, but we find it to be the least-cost integration strategy for 10% of feeders. In over 80% of those feeders, the amount of downsizing that would be required is less than 20%.

Takeaways: CS integration solutions (2)

- As currently sized, CS can reduce line losses by 10 to 20% in primary distribution feeders.
- Strategic siting within a feeder can substantially reduce interconnection costs and reduce the need for downsizing CS projects. This suggests that joint evaluation between CS developers and utilities would lead to the best project locations.

Policy and regulatory insights

- Given that CS does not require distribution system upgrade costs on most of our modeled feeders, the hosting capacity benchmark for minimum daytime load to size CS may be too conservative. Requiring utilities to perform more rigorous hosting capacity analysis may identify larger sizes for CS projects that still avoid distribution upgrade costs.
- Regulators could require utilities to identify feeders that are candidates for non-wires alternatives like CS for capacity deferrals (e.g., for electrification or large lump loads), so CS developers can target these feeders for project siting. Shared-savings mechanisms could incent utilities to work with CS developers to achieve capacity deferral benefits on those feeders, while providing savings to utility customers.
- CS requirements could include CS project downsizing guidelines to reduce interconnection costs for CS developers.
- Utilities could be required to work with developers to identify feeder locations that are more strategic for siting CS projects.

Potential Future Research

Potential future research (1)

- Revenue impacts from the developer's perspective of: (1) downsizing CS projects (taking <u>our results</u> as an input) and (2) optimal sizing of CS projects.
- Rate impacts of ratebasing some grid upgrades for CS, including:
  - ratebasing costs up to the cost reduction benefits of deferring distribution system capacity (e.g., for meeting large new customer loads), leading to neutral (or negative) rate impacts;
  - providing guidelines utility regulators can consider for selecting the types or shares of CS-related distribution system upgrades most suitable for ratebasing consideration.
- Best practices for interconnection queuing: Identify potential grid upgrades that can create synergies and enable the interconnection of multiple CS projects;
- Analysis of how electrification trajectories may increase the potential–and reduce interconnection costs–of CS projects.

Potential future research (2)

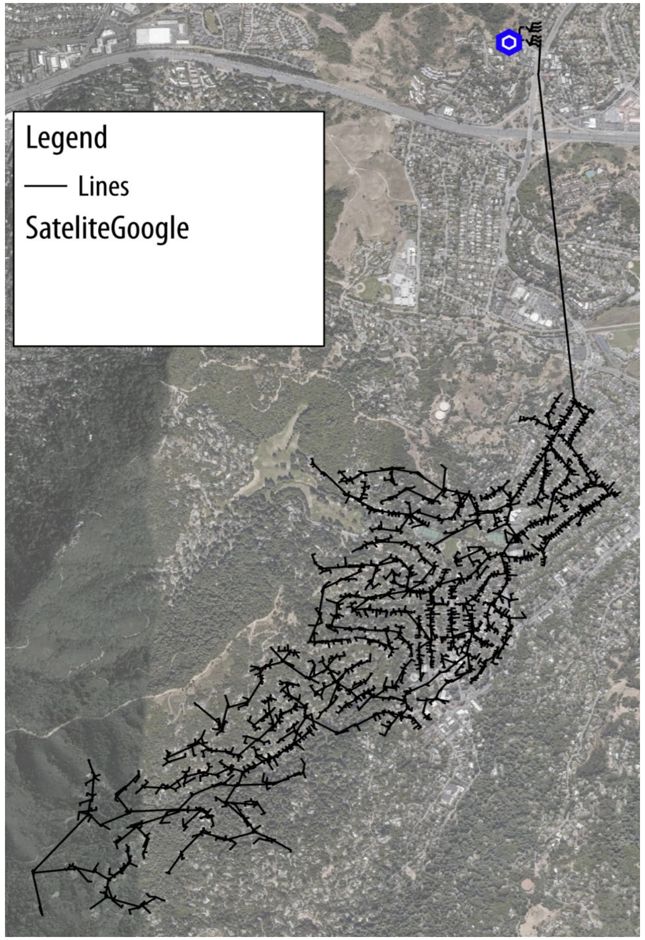
- Grid impact costs from the CS developer's perspective, assessing effects on economic returns, as well as economic impacts from the utility's perspective.
- CS compensation methods that better reflect wholesale costs of CS systems and drive distribution grid-optimal decisions, including changes in subscriber and CS credit methods (commonly used bill credit structures, for example, do not incentivize pairing CS with battery storage).
- Pros and cons of promoting rooftop PV vs. CS in terms of benefits for the distribution grid.
- Distribution-connected CS as a strategy to increase PV deployment in the face of high costs and long queues for transmission-level interconnection.

Appendix. Case Examples

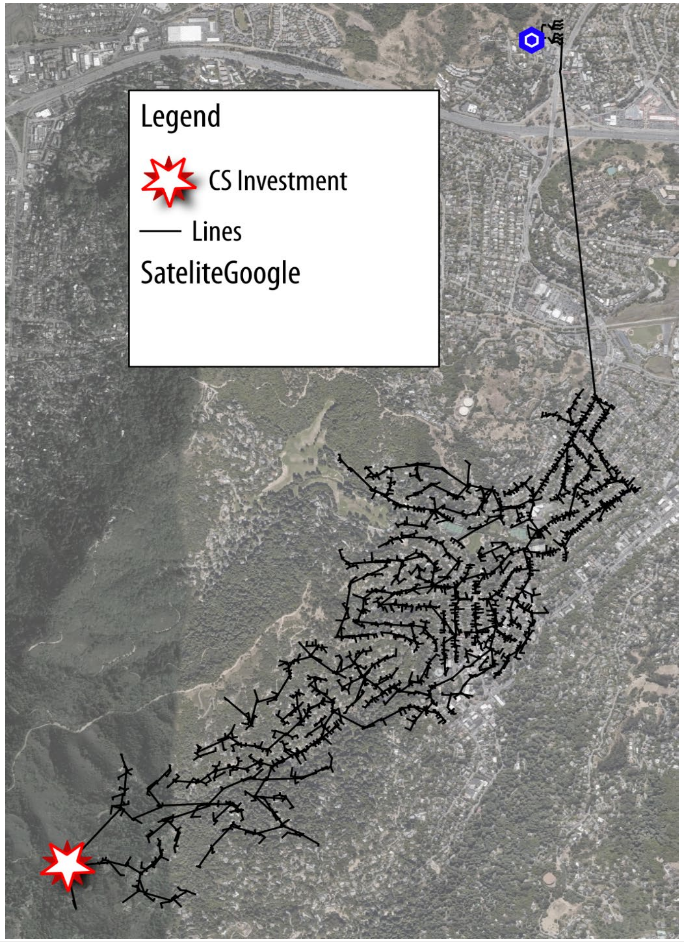
How do CS impacts change across different feeder types?

Base Case

Feeder without CS



Feeder with CS



SFO Feeder

- Peak Load 4.5 MW
- CS: 1.7 MW

No CS impact on feeder upgrades

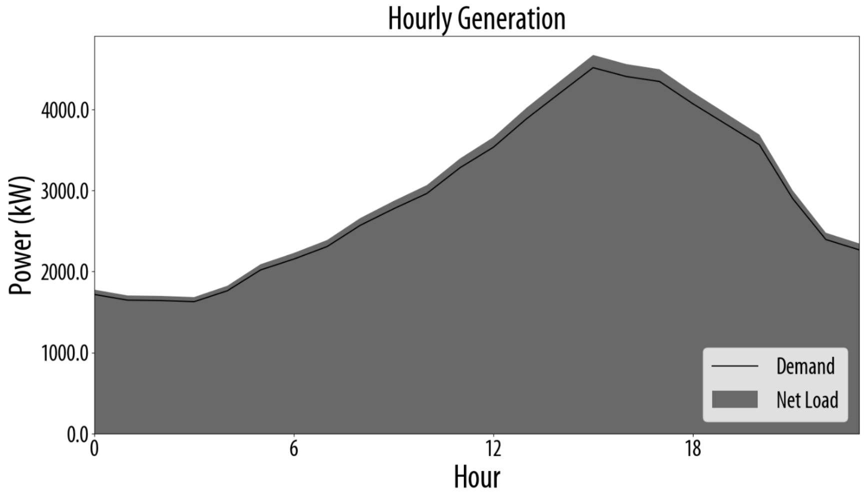
Investments	Without CS	With CS	Impact
Lines (miles)	0	0	0
Storage MWh	0	0	0
Transformer Upgrade	No	No	0
Total (k$)	0	0	**0**

A moderately loaded feeder (far from its hosting capacity limits) does not require any feeder upgrades.

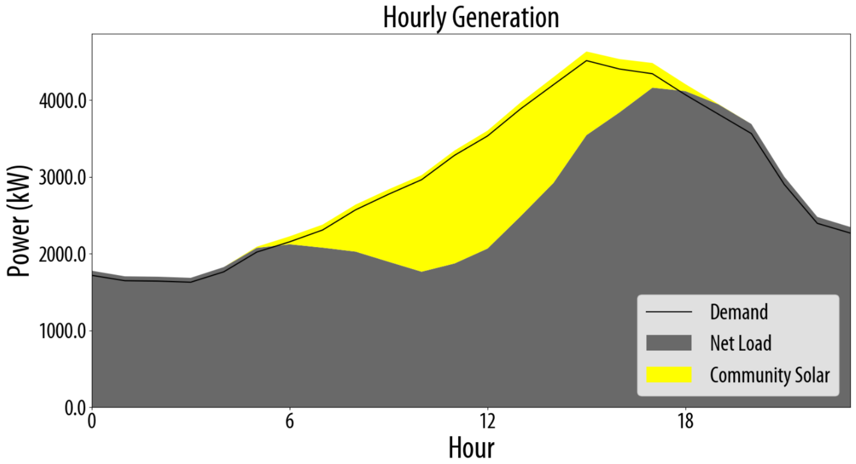
A CS project, interconnected at the end of the feeder, and sized equal to the minimum daily load (MDL) allows the feeder to operate within the technical limits and no upgrades are required.

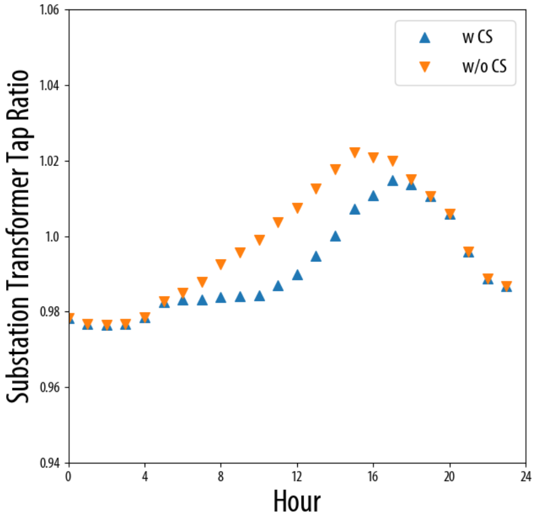
Base Case: Operation

Netload without CS

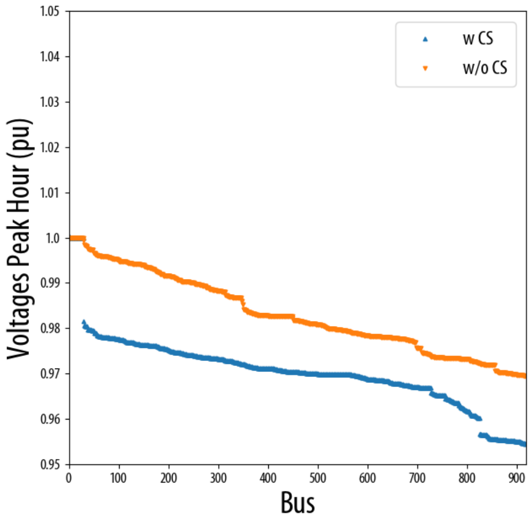


Netload with CS





Substation transformer tap ratio throughout the day.

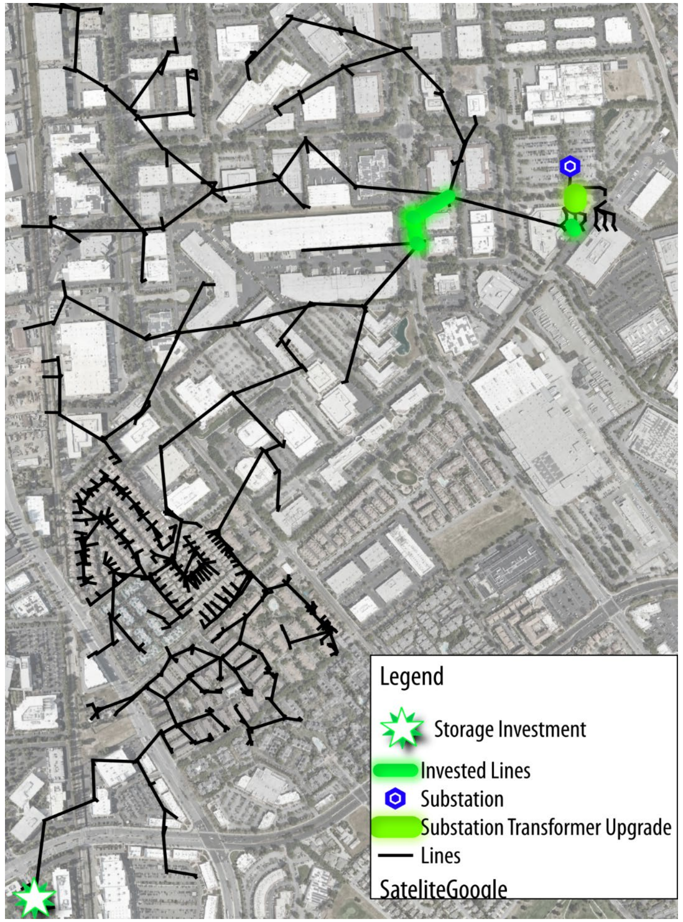


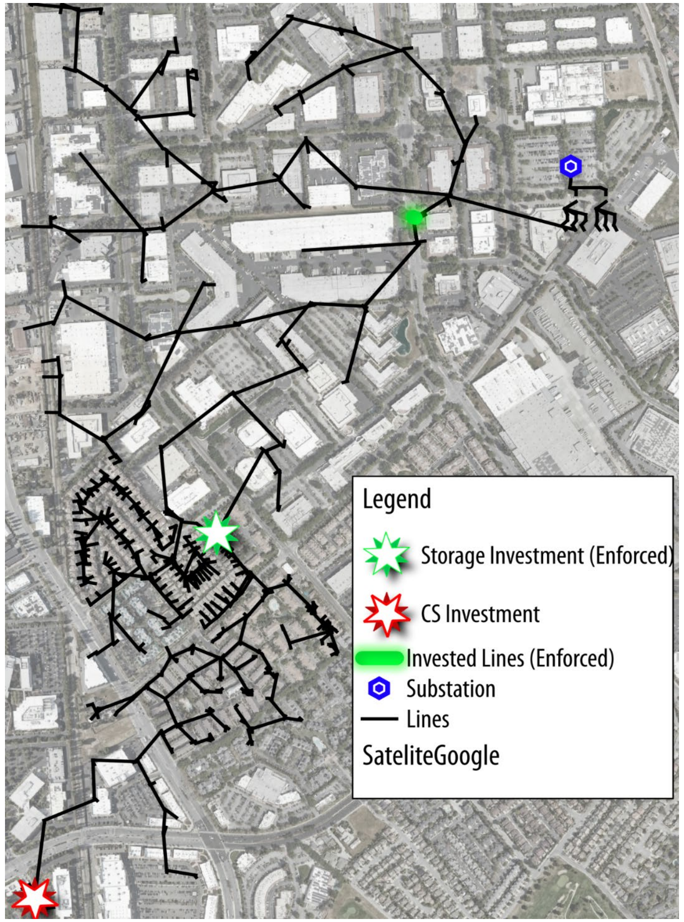
Comparison of the voltage profile across the 900 nodes during the peak hour.

The interconnection of the CS project at the end of the feeder helps alleviate undervoltage at the peak hour and reduces the need for voltage control via the substation transformer tap.

The presence of CS improves the feeder operation and does not require additional investments.

Load Case





SFO Feeder

- Peak Load 17.9 MW
- CS: 6.5 MW

CS defers $648k in investments

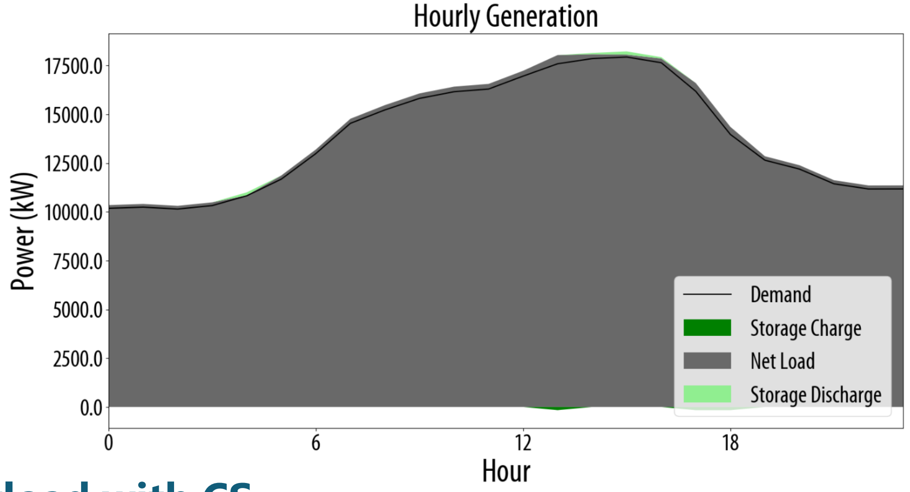
Investments	Without CS	With CS	Impact
Lines (miles)	0.1	0.001	-0.1
Storage MWh	0.32	2.27	1.95
Transformer Upgrade	Yes	No	Deferred
Total (k$)	2,086.1	1,438.2	**-647.9**

A heavily loaded large feeder needs capacity upgrades at the top combined with storage at the end of the feeder.

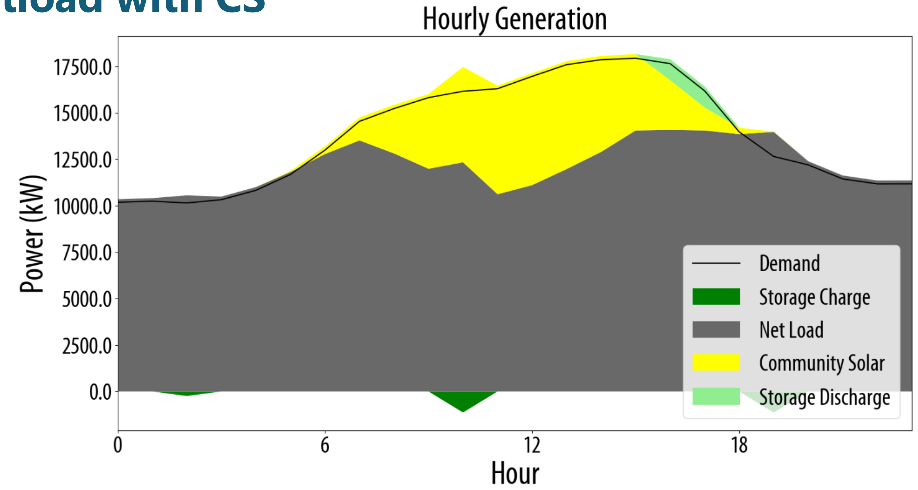
When a CS project is installed at the end of the feeder, storage placed in the middle of the feeder is sufficient to avoid reconductoring investments.

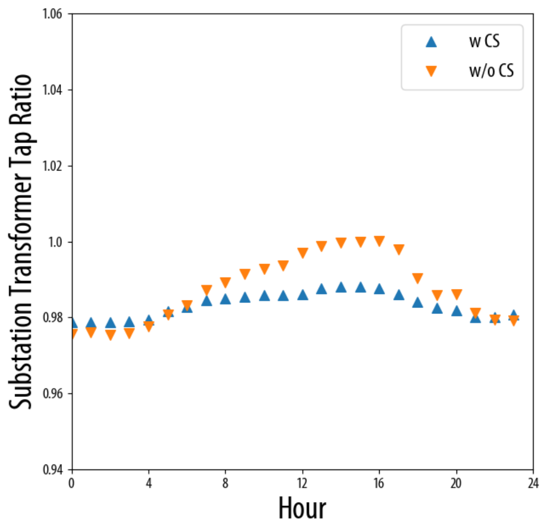
Load Case: Operation

Netload without CS

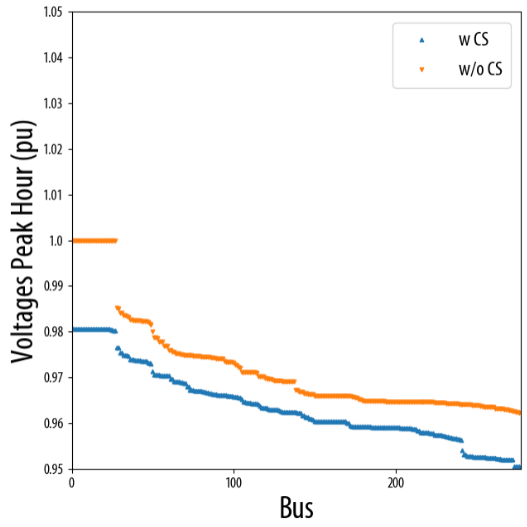


Netload with CS





Substation transformer tap ratio throughout the day.



Comparison of the voltage profile across the 300 nodes during the peak hour.

The presence of CS at the end of the feeder combined with a storage project in the middle of the feeder improves voltage control.

Storage discharges in the evening to compensate for the PV ramp down during the peak hour. This reduces the peak and the need for upgrades.

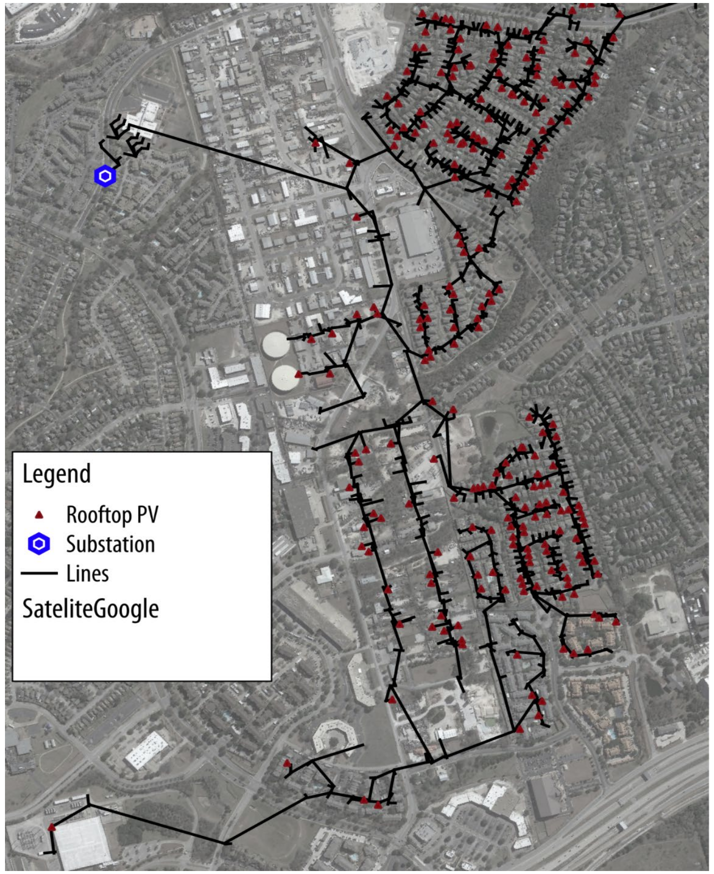
PV Case

AUS Feeder

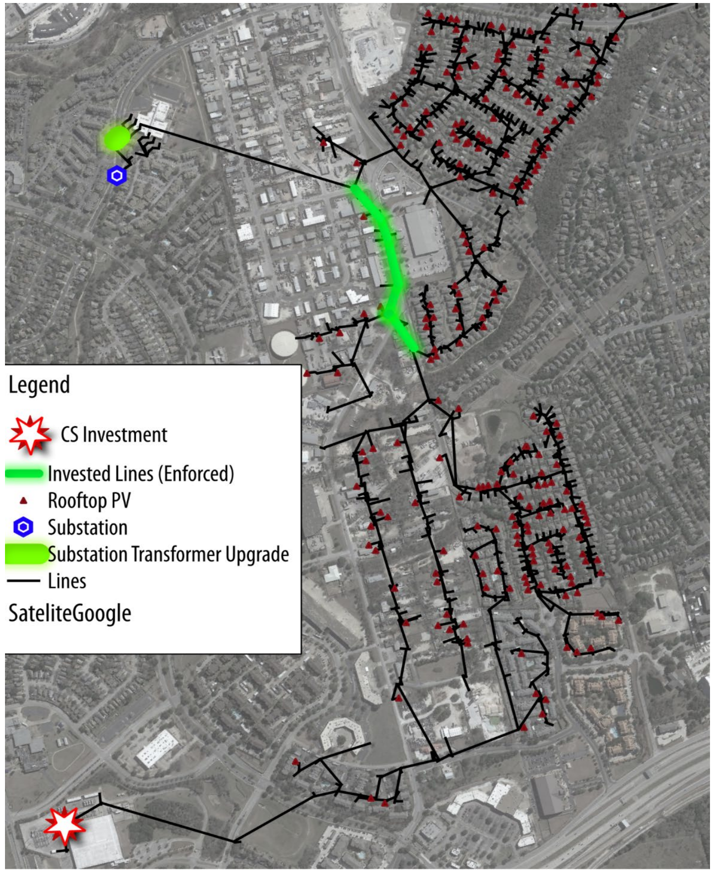
- Peak Load: 8.2 MW
- Rooftop: 10 MW
- CS: 3.1 MW

CS requires $407k in upgrades

Feeder without CS



Feeder with CS



Investments	Without CS	With CS	Impact
Lines (miles)	0	0.37	-0.37
Storage MWh	0	0	0
Transformer Upgrade	No	No	0
Total (k$)	0.0	407	**-407**

A feeder with pre-existing rooftop PV installations is near its hosting capacity limits.

An 3 MW CS project installation requires reconductoring a significant portion of the central part of the feeder, which results in an interconnection cost of $407k.

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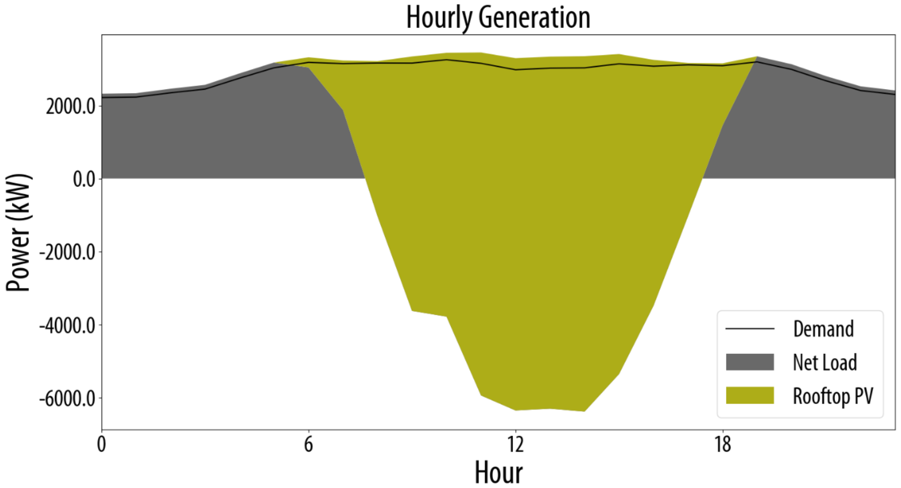
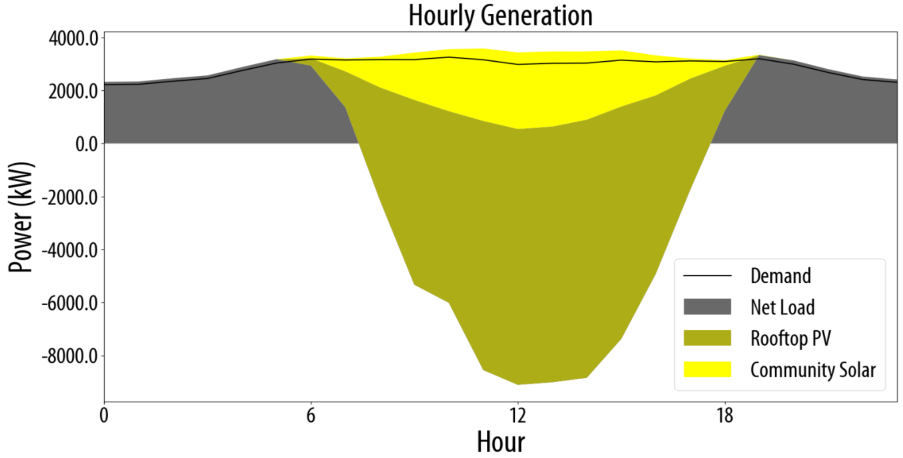
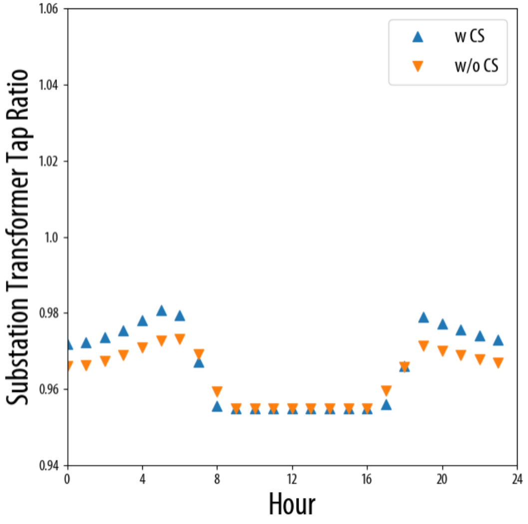
PV Case: Operation

Netload without CS

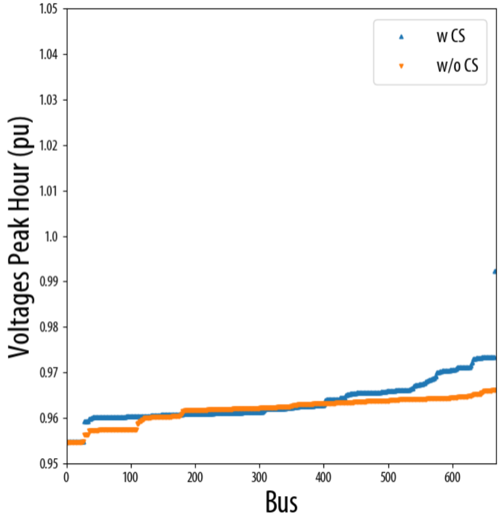


Netload with CS





Substation transformer tap ratio throughout the day.



Comparison of the voltage profile across the 700 nodes during the peak hour.

Given the density of the feeder, the voltage profile is not significantly affected by the presence of rooftop solar.

When a CS project is added to the feeder, the reverse power flow becomes higher than the system peak, requiring new capacity upgrades.