EFFECTS OF ROOFTOP SOLAR ON THE DISTRIBUTION GRID: EVIDENCE FROM CONNECTICUT

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Overview

This paper quantifies the effect of distributed solar generation on distribution feeders using unique, proprietary data from individual solar installations and feeders in Connecticut. We find that each additional kilowatt (kW) of distributed solar reduces the annual maximum feeder load and the top one percentile of feeder load by 0.11 kW. Using a matched difference-in-differences approach, we also find evidence of a 3.6% solar rebound effect, primarily occurring in spring and fall. Importantly, this rebound does not affect the impact of distributed solar on peak feeder loads, as these predominantly occur during the summer. Except in high-congested feeders, the economic value of deferred distribution capacity investment ranges from $0.3 to $2.9 per MWh, significantly below the cost premium of distributed solar compared to utility-scale solar. Our findings imply that even in a summer-peaking system, distributed solar generation cannot be rationalized solely by savings from deferred distribution feeder investments.

Methods

The study combines several datasets, including:

- Annual maximum loading data for 233 low-voltage feeders (2010–2019).
- Hourly loading data for 26 feeders (2019).
- Hourly solar generation data for 10,266 installations (2016–2021).
- Household-level injection and withdrawal data for 361 homes (2019–2020).

First, We combine the three datasets of annual maximum feeder loading, hourly residential solar generation, and local utility total loading profiles in the overlapping period from 2016 to 2019 to estimate the impact of residential solar installation on annual feeder peak load. In the initial specification, we directly calculate the impact of solar energy on reducing the annual peak load of the feeder as the solar generation at the feeder's observed annual peak hour. We then calculate the percentiles of the annual distribution of hourly feeder loads using the same methodology, but only using the 26 feeders for which we have hourly loading data.

To estimate the effect of solar adoption on electricity consumption patterns, we use three datasets: hourly electricity injection and withdrawal for 63 solar households, hourly solar generation for all residential solar panels, and hourly electricity withdrawal for 298 non-solar control households in the same utility service area. For the difference-in-differences (DID) analysis, 27 solar households with at least three months of data before and after solar installation were selected. The start date of treatment is inferred from the first injection records. To create comparable treated and control groups, we use three-nearest-neighbors propensity-score matching based on pre-solar-installation electricity consumption patterns. To test the parallel trend assumption of the DID, we conduct an event study on the monthly net consumption (which equals the difference between withdrawal and injection). We regress the monthly net consumption (or the log of monthly net consumption) on the interaction terms between the treatment group indicator and a vector of month dummies controlling for month-of-sample fixed effects, day-of-week fixed effects, hour-of-day fixed effects, and household fixed effects. The standard error is clustered at the household level.

We conduct two main robustness checks. First, we conduct a sensitivity analysis by using different levels of solar rebound effects. Second, we use reduced-form regressions, similar to Astier et al. (2023), to estimate the impact of solar installations on annual peak load across 233 feeders from 2010 to 2019, controlling for customer numbers and including fixed effects. Using Two-Stage Least Squares (2SLS) with instrumental variables derived from randomized "Solarize" campaign timing, we find a coefficient of -0.67 for cumulative solar capacity (p-value: 0.596), which, despite its imprecision, aligns with our primary findings

Results

The findings reveal that rooftop solar reduces annual peak feeder loads by 0.11 kW per kW of installed capacity. This contribution diminishes with higher solar penetration, stabilizing at 0.04 kW per kW when solar installations exceed 28% of households. Distributed solar reduces load percentiles, with the greatest impacts on higher percentiles, aligning with its effectiveness during peak summer demand periods.

The solar rebound effect was found to average 3.6%, primarily occurring during midday in spring and fall, without affecting peak feeder loads. The rebound effect's temporal and seasonal characteristics were estimated using hourly household-level consumption data.

Economic analysis shows that the value of deferred distribution capacity investments ranges from $0.3 to $2.9 per MWh across most feeders. For highly congested feeders nearing capacity limits, this value can rise to $71.6 per MWh, potentially making distributed solar cost-competitive with utility-scale solar under specific conditions. However, such benefits are limited to a small subset of feeders. To incentivize investment in solar installations within these constrained feeders, policy measures could include targeted subsidies, feed-in tariffs, tax incentives, or public campaigns specifically designed for regions at capacity limits.

Finally, we studied how the contribution of solar capacity to feeder peak loading may change as the solar installation rate increases. We find that the maximum load (kW) reduction per kW of solar remains consistent at 0.08 and the top 1% load at 0.11 up to solar penetration levels of 5.6%. Beyond this, the average solar capacity contribution starts to diminish but flattens out at 0.04% for the maximum load and at 0.08 for the top 1% load.

Conclusions

This paper is the first to utilize actual data from individual solar installations and their hourly generation, as well as feeder loading, to estimate the impact of distributed solar on the distribution network. We find that an additional kW of distributed solar decreases maximum annual feeder load and top 1% of feeder load by around 0.11 kW on average. The capacity contribution shows heterogeneity across time: it is highest for feeders peaking in June at around 30%, around 11% on average for feeders peaking in July or August, and almost zero in other months. The economic value of avoided distribution capacity ranges from $0.3 to $2.9 per MWh, aligning with estimates from other less-data intensive studies. These benefits fall short of the additional costs associated with distributed solar power when compared to utility-scale solar.

The findings of this paper highlight several key policy implications. First, it is possible to calculate solar's capacity contribution, but this requires detailed hourly grid and solar generation data. Second, these empirical values can be used when replacing current net-metering policies with alternative tariff structures to better align solar incentives with grid benefits. Lastly, policymakers might consider encouraging targeted solar installations in feeders nearing capacity limits, where the economic value of deferred upgrades is highest, possibly through region-specific subsidies or incentives.