

Solar Adoption by Mandates

Stefano Carattini, Wade Davis, and Anton Heimerdinger

33rd Young Energy Economists and Engineers Seminar

May 2024

*Results preliminary. The views expressed in this paper are the authors' own and do not necessarily represent those of the U.S. Environmental Protection Agency (EPA). In addition, the research described in this paper has not been subjected to the Agency's required peer and policy review. No official Agency endorsement should be inferred. All errors and omissions are the authors' own.

Rooftop solar panel mandates for new construction

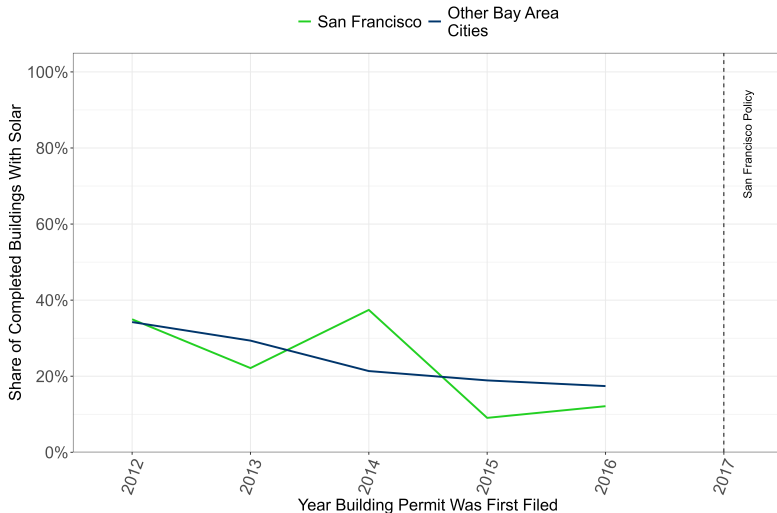
Building codes for new construction are an increasingly common policy mechanism to encourage the transition away from fossil fuels. E.g., residential gas bans, energy efficiency standards, and rooftop solar panel mandates.

- **California:** Since 2020, the California Energy Commission (CEC) has required rooftop solar for residential new construction buildings.
- **European Union:** European Parliament has passed a rooftop solar mandate to be phased in by 2030.
- **Municipal policies:** **California:** San Francisco (2017 implementation), Brisbane, Culver City, Davis, Fremont, Lancaster, San Mateo, Santa Monica, San Mateo, Sebastopol. **Florida:** South Miami. **Germany:** Baden-Württemberg, Berlin, Hamburg.

What has motivated these mandates?

- Various policy goals: electrification and substitution away from fossil fuel, as well as more specific goals. E.g., city-wide carbon-neutrality and “zero net energy” buildings.
- Cost-effectiveness reports have suggested that solar is universally cost-effective on new construction. But do new buildings universally adopt solar?

Pre-policy solar adoption (residential new construction)



Other Bay Area cities include Daly City, Danville, Oakland, San Jose, Santa Rosa, and unincorporated San Mateo County.

[Post-policy](#)[By city](#)

Research questions (1 of 3)

1) Evaluation of private payoffs:

- What are the distributions and magnitudes of the payoffs (NPVs) across project characteristics?
- Do the cost-effectiveness approaches used to motivate the mandates miss important heterogeneity?
- We apply an engineering model, National Renewable Energy Laboratory (NREL) System Advisor Model (SAM), across a dataset of over 6,000 building permits, using detailed project-level characteristics.

Research questions (2 of 3)

2) Evaluation of a “solar gap:”

- Are builders leaving money on the table?
- Do cost-effectiveness approaches miss non-monetary costs, such as hassle and uncertainty, which may lead to an *apparent* solar gap?
 - To evaluate these potential mechanisms and other sources of engineering model misspecification: We compare (i) solar NPVs with total project costs and (ii) NPVs across model assumptions.
- Once accounting for potential sources of an *apparent* solar gap, is there still any evidence of an *actual* solar gap?
 - As in the broader energy efficiency gap literature, a “solar gap” could arise from some behavioral or institutional friction. E.g., incomplete capitalization of solar payoffs in real estate or rental markets.
 - To explore the “solar gap,” we compare engineering estimates to observed solar adoption decisions.

Research questions (3 of 3)

3) Policy evaluation:

- How much have mandates increased new construction solar adoption?
- Exploiting the variation in policy designs and timing, we compare canonical difference-in-differences to staggered DiD, synthetic control, and regression discontinuity at city borders.
- Today, we focus on Bay Area cities and the frontrunner San Francisco policy. In ongoing work, we can also evaluate other frontrunner policies as well as California's statewide policy.

Note on welfare

Literature

Energy efficiency gap: Hausman (1979); Allcott and Greenstone (2012); Gillingham and Palmer (2014).

- **Ex-post comparisons to engineering estimates:** Davis et al. (2014); Fowlie et al. (2018).

Cost-effectiveness of building codes: Levinson (2016); Kotchen (2017); Carattini et al. (2022).

Solar adoption decisions: Bollinger and Gillingham (2012); Dong et al. (2023).

Evaluation of distributed solar policies: Borenstein (2012); Ovaere and Gillingham (2022).

Our contribution: Rooftop solar mandates are largely unstudied (aside from ex-ante engineering reports). We explore impact of these new and understudied policies and also introduce and investigate the question of whether there exists a “solar gap.”

Agenda

- Data: California Bay area new construction project characteristics
- Evaluation of private payoffs
- Evaluation of a solar gap
- Policy evaluation

Data summary

Building permits: New construction building permits collected from individual municipalities. Permits include project locations, solar adoption decision, and other building characteristics.

- Today, we focus on residential new construction projects in a sample of Bay area cities: San Francisco, Daly City, Danville, Oakland, San Jose, Santa Rosa, and unincorporated San Mateo County.

Other data for SAM estimation of private payoffs:

PG&E: Sample of new construction electricity billing data from PG&E. Also, historical tariffs and solar compensation rates.

Google Sunroof: Roof characteristics including roof size and shading.

NREL:

- National Solar Radiation Database (NSRDB): Typical meteorological year (TMY) files.
- OpenEI: Historical electricity tariffs.
- SAM archives: Historical SAM parameters, including installation costs. Alternate installation cost data from California Solar Initiative and building permits.

Residential new construction permits

	San Francisco	Other Bay Area Cities
All permits filed 2012-2019		
Number of active and complete permits	1,388	4,638
Number of complete permits	876	3,054
Pre-policy permits filed 2012-2016		
Number of active and complete permits	1,002	2,876
Number of active and complete permits with solar	193	624
Number of complete permits	782	2,521
Number of complete permits with solar	180	581
Share of complete permits with solar	23.02%	23.05%

Table of residential new construction projects. See data discussion for list of sample cities.

Post-policy

By city

Evaluation of private payoffs

Private cost-effectiveness: engineering method

Consider an engineering model M (e.g., NREL's SAM) that estimates the value $V_{i,\tau}$ of a solar project i installed at time τ

$$V(s_i, X_{i,\tau}) = \sum_{t=\tau}^{\tau+T} \beta^{(t-\tau)} M(s_i, X_i, \zeta_t)$$

- where s_i is the size (kW) of the solar system; $X_{i,\tau}$ are building project characteristics; ζ_t are the model's default assumptions and parameters; β is a discount factor; and T is the life of the system.

A builder chooses the system size s_i^* to maximize their expected payoff

$$s_i^* = \arg \max_{s_i \geq 0} \mathbb{E}_\tau \left[V(s_i, X_{i,\tau}) \right]$$

- where the builder forms their expectations about the system's future performance and payoff in the same period τ as their initial investment decision.

Data sources and illustrative SAM example

This table summarizes our data sources and an example SAM parameterization for a project in our data. **NPV components**

Parameter	Illustrative value	Data Source
SAM inputs		
Time horizon	25 years	SAM default
Global horizontal irradiance	4.73 kWh/m ² /day	NSRDB database (4km×4km cells)
Shading	3%	Estimated using Google Sunroof
Installation cost	\$3.29/watt-DC	Annual time series of SAM defaults
Interest rate on loan	5%	Annual time series of SAM defaults
Solar owner discount rate	6.4%	SAM default
Federal Investment Tax Credit (ITC)	30%	SAM default
Electricity tariff	2018 PG&E time-of-use	NREL OpenEI database and PG&E
Compensation rate for excess generation	\$0.03/kWh	PG&E time series
Electricity consumption (monthly average)	445 kWh	Sample of PG&E billing data (hourly)
Estimated to maximize SAM NPV		
System capacity	4 kW	Estimated
SAM outputs		
Electricity production (monthly average)	509 kWh	Estimated
Electricity bill without solar (monthly average)	\$106	Estimated
Electricity bill savings with solar (monthly average)	\$95	Estimated
Total installed cost	\$13,160	Estimated
Net present value of solar investment (NPV)	\$5,815	Estimated

NPV distribution, residential new construction 2012-2016

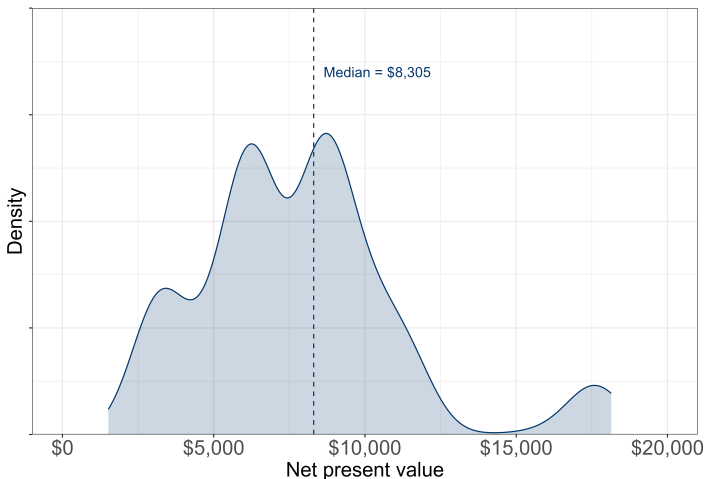


Figure includes only completed residential new construction projects. See data discussion for list of sample cities.

Multifamily

5kW

Higher costs

What are the magnitudes and distributions of solar payoffs?

Findings from the distributions of estimated payoffs:

- There is substantial heterogeneity in building project characteristics and project payoffs.
- Private payoffs are generally positive. This finding is robust across a variety of alternative parameterizations and model sensitivities.
- However, the payoffs are small relative to the total costs of the new construction projects.
- Although the finding of positive payoffs is robust, payoff estimates are sensitive to alternative parameterizations.
- The sensitivity of the models suggest builders may also face uncertainty when making their solar adoption decisions.

Evaluation of a “solar gap”

Evaluation of a “solar gap”

Do builders forego solar despite positive expected payoffs? Could these apparently foregone payoffs be explained by hidden or non-monetary costs?

We proceed with a descriptive comparison of observed solar adoption decisions to estimated expected payoffs $\hat{v}_{ict}$, estimating the linear probability model

$$y_{ict} = \beta_0 + \beta_1 \hat{v}_{ict} + \mathbf{x}'_{ict} \beta_2 + \epsilon_{ict}$$

- where y_{ict} is the observed solar adoption decision for project i in city c and year t .
- $\mathbf{x}_{ict}$ are covariates that may suggest mechanisms for a perceived “solar gap.”

Remark: Where $\hat{v}_{ict}$ is estimated with no misspecification and there is no “solar gap,” $P(y_{ict} = 1 | \hat{v}_{ict} > 0) = 1$.

NPV distributions with and without solar, 2012-2017

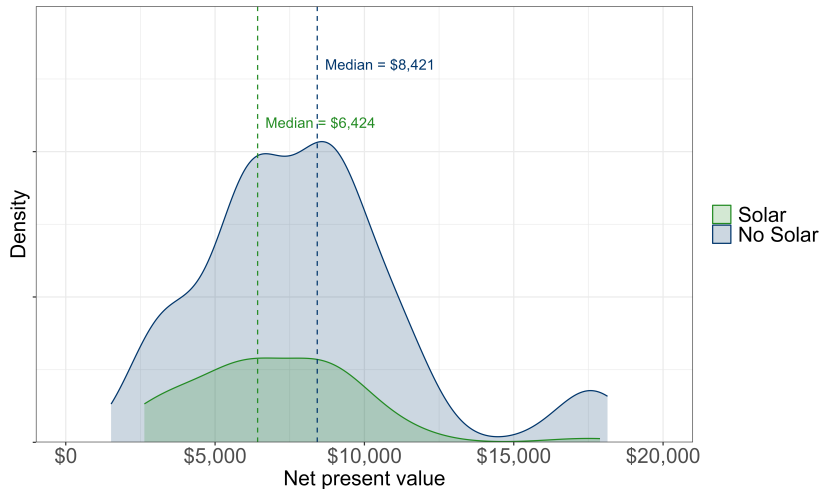


Figure includes only completed residential new construction projects. See data discussion for list of sample cities.

[5kW](#)[Higher costs](#)

Estimated NPV and solar adoption decision

Net present value (NPV) (\$1,000s)	-0.021*** (0.003)	0.015 (0.015)	0.020 (0.015)	0.018 (0.016)
Income (\$1,000s)				0.001*** (0.000)
Multifamily				-0.068 (0.036)
Num.Obs.	1819	1819	2106	1527
R2	0.029	0.102	0.086	0.112
R2 Adj.	0.029	0.096	0.080	0.105
City fixed effects	No	Yes	Yes	Yes
Year fixed effects	No	Yes	Yes	Yes
Restrict years: 2012 to 2016	Yes	Yes	No	Yes
Include San Francisco after 2016	No	No	No	No

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Outcome is indicator for solar adoption. Median income is from the Census block group.

Is there evidence of a “solar gap”?

Findings from the relationship between observed solar adoption decisions and estimated payoffs:

- Payoff estimates are generally positive across the distribution of building projects.
- Most new construction buildings do not adopt solar, despite engineering estimates suggesting positive payoffs.
- Failure to adopt solar is prevalent across the distribution, even among buildings with the highest estimated payoffs.
- We do not find a relationship between payoffs and the solar adoption decision, suggesting that there may be other determinants of the solar adoption decision than the private payoff.
- These findings are robust to a variety of alternative engineering model parameterizations.

Policy evaluation

How much have mandates increased solar adoption?

Our evaluation explores three settings:

- (i) San Francisco, the largest frontrunner city (2017 implementation); (ii) other frontrunner cities (*ongoing*); and (iii) California's statewide policy (*ongoing*).

We explore the policy's effect on new construction solar adoption:

- 1 Descriptive summary statistics and time series.
- 2 Comparing canonical difference-in-differences to three alternative estimators:
 - 1 Staggered difference-in-differences exploiting the handful of Bay Area municipalities that adopted a solar mandate prior to the 2020 statewide policy (*ongoing work*);
 - 2 Synthetic control with a donor pool of Bay Area cities (*ongoing work*);
 - 3 Sharp regression discontinuity exploiting the border between San Francisco and Daly City (*ongoing work*).

Pre- and post-policy solar adoption

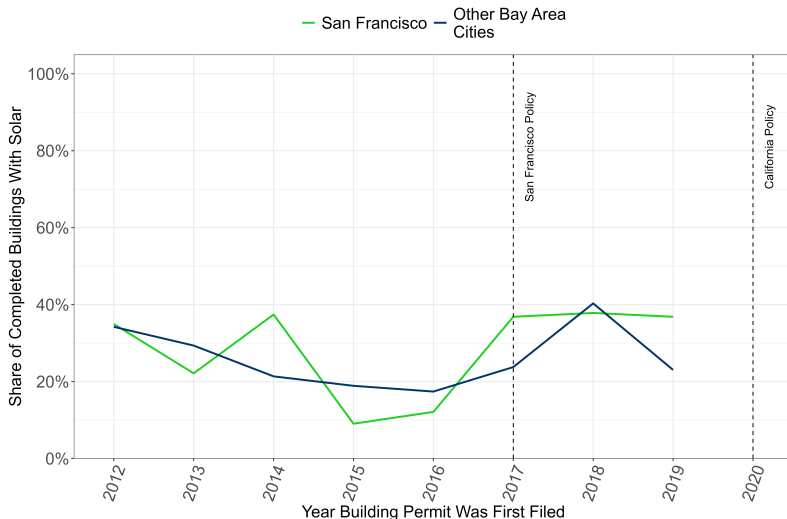


Figure includes only completed residential new construction projects. See data discussion for list of sample cities. [By city](#)

Residential new construction permits

	San Francisco	Other Bay Area Cities
<u>Permits filed 2012-2016</u>		
Number of active and complete permits	1,002	2,876
Number of active and complete permits with solar	193	624
Number of complete permits	782	2,521
Number of complete permits with solar	180	581
Share of complete permits with solar	23.02%	23.05%
<u>Permits filed 2017-2019</u>		
Number of active and complete permits	386	1,762
Number of active and complete permits with solar	47	260
Number of complete permits	94	533
Number of complete permits with solar	35	146
Share of complete permits with solar	37.23%	27.39%

Table of residential new construction projects. See data discussion for list of sample cities.

Post-policy

By city

Conclusions

- **Evaluation of private payoffs:** Engineering estimates of payoffs are generally positive, though with substantial heterogeneity that has been neglected in earlier engineering studies. Payoffs are small relative to overall new construction project costs.
- **Evaluation of a solar gap:** The majority of new construction buildings do not adopt solar, despite engineering estimates suggesting positive payoffs. We also fail to find a relationship between payoffs and the solar adoption decision. Given the robustness of these findings to alternative engineering model parameterizations, these results provide evidence that there may indeed be a “solar gap.”
- **Policy evaluation:** Many new construction buildings fail to adopt solar even after policy implementation, suggesting that builders avail themselves of the flexible policy design and exemptions.

Ongoing work: We are continuing to develop alternative engineering model parameterizations and implement a series of specifications to estimate the policy effect.

APPENDIX

Note on welfare

Today, we focus on the *private payoffs* of solar adoption and the hypothesis of a “solar gap.”

A complete welfare evaluation of a distributed generation policy, would require several additional considerations:

- Changes in emissions and effects on the electricity grid (e.g., costs of the distribution network).
- Transfers from Federal and State incentives.
- “Cross-subsidization” among electricity customers arising from the net metering policy.
- Interactions with existing policy. E.g., California and the EU have cap-and-trade policies.

Counts of active and complete permits by municipality

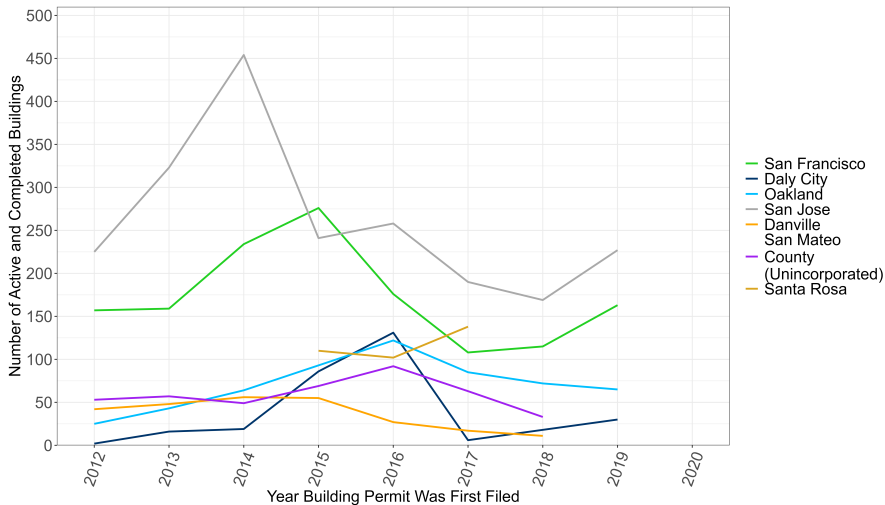


Figure includes only residential new construction projects.

[Return](#)

Solar adoption shares by municipality

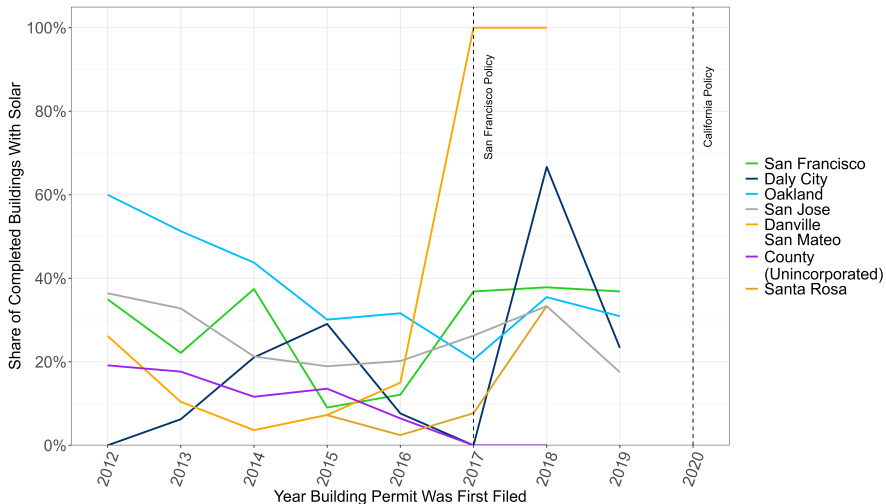
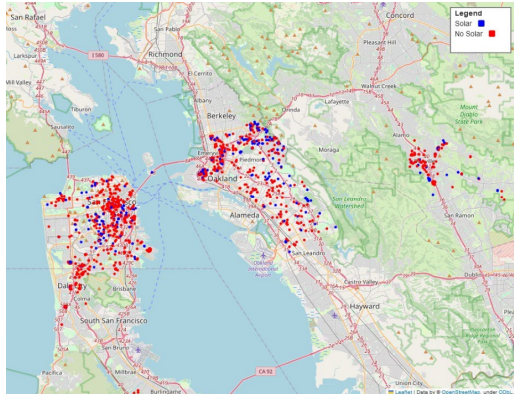
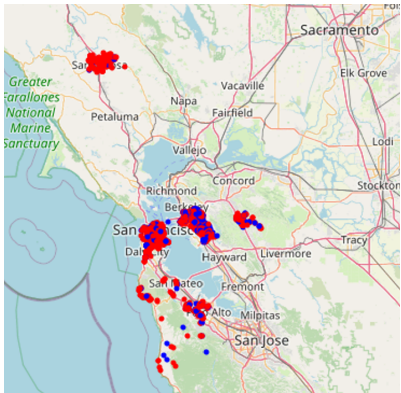


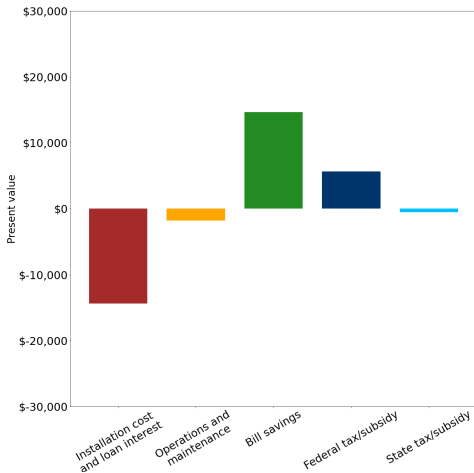
Figure includes only completed residential new construction projects.

[Return](#)

Permit locations



NPV components (illustrative example)



NPVs, multifamily new construction, 2012-2016

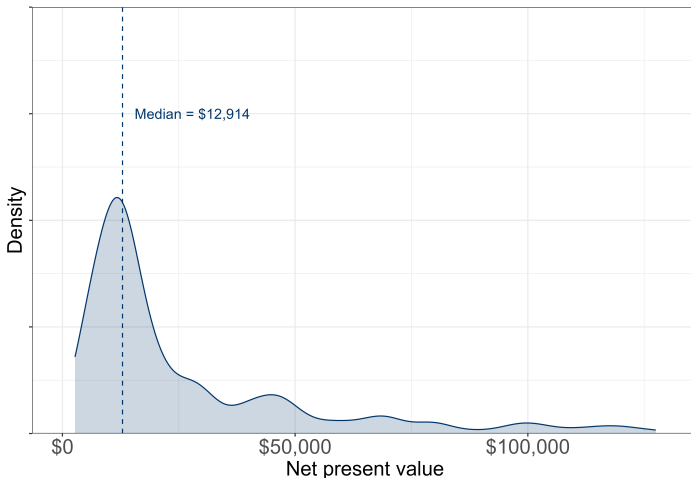
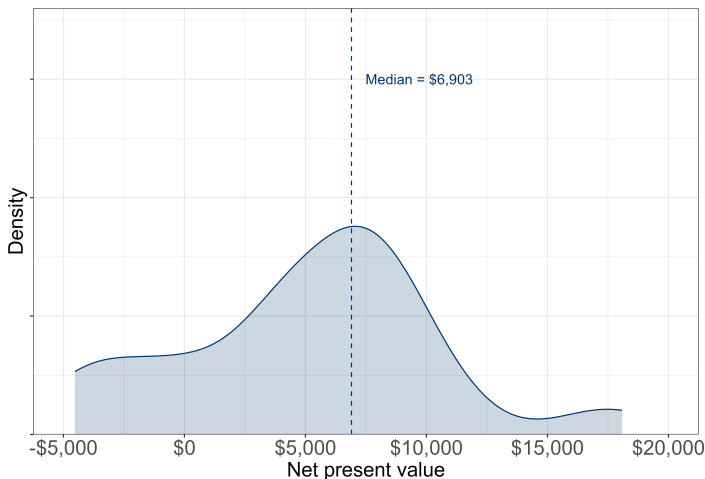


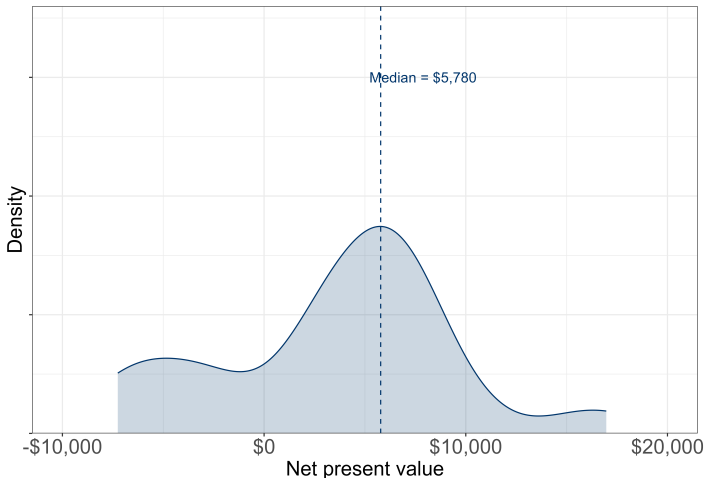
Figure includes only completed residential multifamily new construction projects. See data discussion for list of sample cities. Figure omits 119 projects with estimated system size over 40kW. [Return](#)

NPVs, residential new construction 2012-2016, 5kW



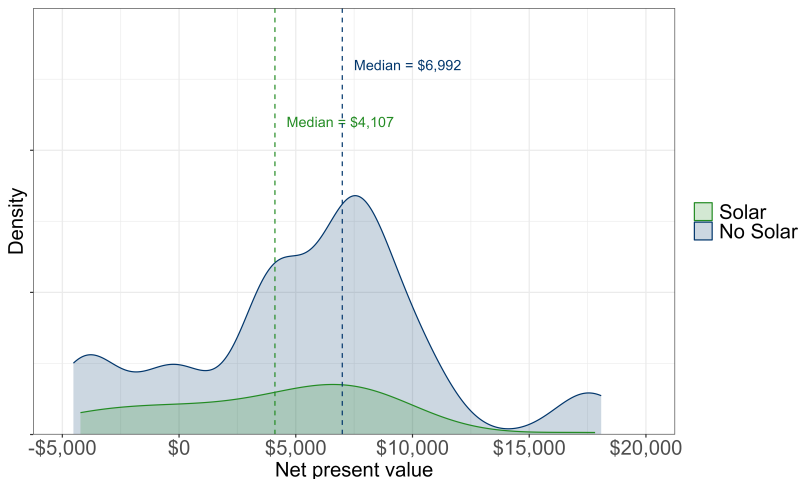
System sizes all constrained to 5kW. Figure includes only completed residential new construction projects. See data discussion for list of sample cities. [Return](#)

NPVs, residential new construction 2012-2016, high costs



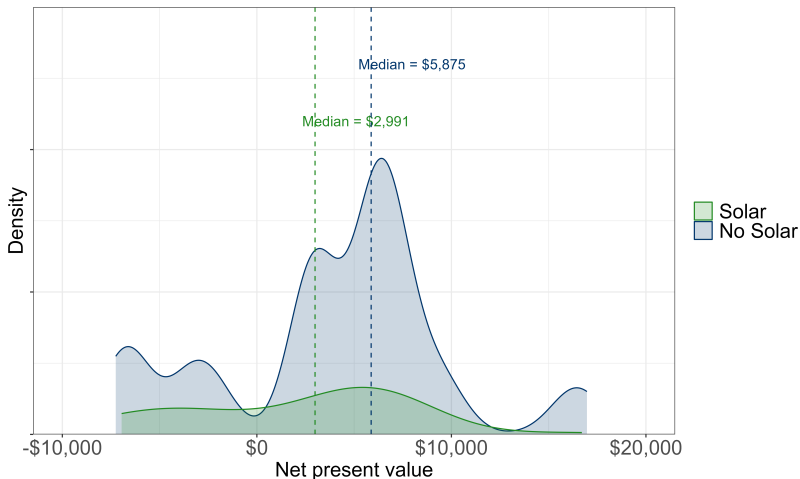
Higher cost assumptions. System sizes all constrained to 5kW. Figure includes only completed residential new construction projects. See data discussion for list of sample cities. [Return](#)

NPVs with and without solar, 2012-2017, 5kW



System sizes all constrained to 5kW. Figure includes only completed residential new construction projects. See data discussion for list of sample cities. [Return](#)

NPVs with and without solar, 2012-2017, high costs



Higher cost assumptions. System sizes all constrained to 5kW. Figure includes only completed residential new construction projects. See data discussion for list of sample cities.