Solar at High Noon: Solar Home Premiums in a Rapidly Maturing Market

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Abstract:
The residential solar market is growing rapidly, with increasing solar installations and solar home resales. In this paper, we explore how current premiums have changed over time, particularly in relation to changes in solar replacement costs and energy savings. We find clear evidence that solar systems are correlated with higher selling prices if those systems are owned by the homeowner (HO). Alternatively, we find no value or slightly lower values associated with non-owned panels. Our estimates show premiums for HO systems have dropped significantly over our study period in the four states we analyze, which is correlated with decreasing replacement costs for similarly sized systems and the overall maturation of the solar market. Notably, as energy costs increase, calculations of projected savings from solar panels now surpass our replacement cost and estimated value premium calculations. Finally, we find that appraisals are more regularly noting solar on homes today but rarely do they provide information on panel ownership structure.

Themes:

- Premiums for solar systems on homes remain prominent, though have shrunk by >50 percent since 2011
- Installation costs are strongly correlated with premiums, more so than potential energy savings, though both provide important market signals
- Non-homeowner owned solar systems do not apparently add value to selling prices
- Appraisers are more frequently flagging solar over time, but as of early 2020 still missed >25 percent of homes

Acronyms:

LBNL	Lawrence Berkeley National Laboratory
CU	Fannie Mae's Collateral Underwriting dataset
Solar	Photovoltaic solar system and/or homes with photovoltaic solar Systems
HO solar	Homes with solar systems that are owned by the homeowner
NHO solar	Homes with solar systems that are not owned by the homeowner, but instead are owned by a third party, such as would be the case for a leased system or one under a power purchase agreement
TTS	LBNL's Tracking the Sun Report, which collects data on individual solar systems covering 80 percent of installed U.S. capacity

1. Introduction

A recent Pew Research Center survey found that 46 percent of homeowners have seriously considered adding solar panels to their homes, on top of the six percent of homeowners who already have solar installed. Of the homeowners considering solar panels, 96 percent reported a desire to use solar energy to save money on utility bills (Pew 2019). This is consistent with broader national trends—residential solar installation capacity has grown by 42 percent per year over the past decade (GTM SEIA 2021) totaling 19 megawatts through 2020. The solar industry estimates 2.6 million households now have solar installed, saving an estimated $1,000 per household and $2.6 billion across all households per year.[1] Overall, energy efficient home improvements have strong support from the building industry, policymakers, homebuyers, and investors. Indeed, California's recent statewide energy efficiency standards requiring solar for all new construction as of 2020 may be a bellwether of these broader institutional and popular trends to come (California Energy Commission 2018a, b). Given this context, this paper examines two key questions: How does the housing market value solar panels? And, has this evolved over the last decade?

Past research has consistently found that solar (also called photovoltaic, or PV) installations are associated with increased housing values.[2] However, the majority of research to date is focused on small geographies or past market cycles, before the broader popularity gains for energy efficient housing features. Solar homes also tend to be newer and located in higher-income and faster-appreciating neighborhoods, and it is often difficult to untangle these factors from the influence of solar installations on value alone. Additionally, housing markets are dynamic, geographically diverse, and influenced by changing market perceptions. Solar technology has evolved over time, becoming vastly less expensive, and state and federal incentives have changed as well. Thus, we contribute to this growing body of literature by examining the influence of solar panels on housing prices and energy savings both over time and across states.

We use a unique dataset—Fannie Mae single-family home appraisal data matched with solar panel installation data from Lawrence Berkeley National Laboratory's (LBNL) Tracking the Sun (TTS) Report Series. These data provide a wealth of information on solar installations and home sales across four states from 2011 through early 2020, allowing us to analyze how premiums for solar homes have changed as various market signals and policies have changed. In addition to this main research question, we also use our unique dataset to outline some salient facts about the role of solar in the housing market, residential energy savings, and home appraisals. First, we explore the influence of leased and Solar Power Purchase Agreement solar on housing values (we refer to these as non-homeowner-owned solar, or NHO, in this paper, but they are commonly known as third-party-owned solar or TPO). Second, we estimate the energy savings for each solar home based on solar panel characteristics and energy costs in its ZIP code. We then use the energy savings data, solar panel installation information, and local sales comparables to compare the different methods of estimating value (comparables, replacement cost, and the income approach based on projected energy savings over time) to determine whether these methods offer comparable estimates of the contribution of solar to housing values. Finally, we examine the extent to which appraisal reports

[1] Using an average solar system size of six KW, system output of 1230 KWh per year/KW—equating to a 17 percent efficiency—and an average U.S. utility rate of $0.135/KWh, results in an annual savings of $1,000.
[2] For example, Dastrup et al (2013), Hoen et al (2013), and Hoen et al (2017), among others.

correctly identify and describe solar in their descriptions of property-specific energy efficient amenities, and whether this has changed over time.

We find clear evidence that solar systems are correlated with higher selling prices if those systems are owned by the homeowner (HO). Alternatively, where they are non-homeowner-owned, we find they do not add value. Premiums for HO systems fall over our study period, which is likely correlated with a corresponding drop in system replacement costs and the overall maturation of the solar market. On the other hand, energy savings from solar units are outpacing premiums and replacement costs. Finally, we find that appraisers are more regularly flagging solar on homes, but rarely indicate the ownership status of the solar unit. We also see that appraised values are higher for solar properties, consistent with the premiums we find using contract prices in our analysis.

The remainder of the paper contains a discussion of prior literature, institutional context, data, and the methodology. Results are then presented, along with a discussion, recommended future work, and conclusions.

2. Literature Review

The broader research on green housing investments in the United States generally finds that energy efficient housing characteristics and/or green labels are associated with housing value premiums. For example, Kahn and Kok (2013) find a 2.1 percent premium associated with green labeled homes from 2007–2012 in California. Goodman and Zhu (2016) find that energy efficient home improvements, including solar, are capitalized into housing prices in California, resulting in higher sales prices. Similarly, Shewmake and Viscusi (2014) find a five percent premium for green label homes in Austin. However, there is evidence of considerable variation in the influence of energy efficient features on housing values across time and space—Walls et al (2013) examine different programs and metropolitan markets and find that premiums vary by local energy costs and certification type. Similarly, Bruegge et al (2016) show that premiums diminished over time for Energy Star-labeled homes in Florida, and note that this may have been due in part to changes in consumer makeup as well as changes in local building codes over time. Most recently, Shen et al (2020) estimate a price premium of $10–17k for homes with heat pumps, but find that premiums are low in areas where heat pump adoption levels are both low and high, which they attribute to both saliency and adoption costs. Collectively, these findings are relevant for our work because of the potential analogous influence of diverse housing markets and consumers on solar premiums over time. They also highlight the importance of controlling for other energy efficient items at the property in our analyses, since these features may also contribute to housing value premiums.

With respect to solar panel installations specifically, research generally finds that solar homes have higher values than other similar homes. However, much of the research is focused on housing values in California, as it is the largest solar market in the United States. For example, Dastrup et al (2013) find a three percent premium for solar homes from the late 1990s through the late 2000s in San Diego. Similarly, Hoen et al (2013) find a premium for solar properties transacting in California from 2000 through 2009.

Solar value premiums are also found in studies using data for other states. In a small multistate study, Adomatis and Hoen (2016) consistently find evidence of single-family residential solar premiums, regardless of state. In a larger study incorporating eight states, Hoen et al (2017) again find evidence of solar premiums, this time amounting to about $15,000 or $4/watt, with similar estimates of the premium regardless of the methodological approach (they use hedonic models, the present value of saved energy costs, and a replacement cost approach).[3] Qiu, Wang, and Wang (2017), show premiums associated with solar home valuations in Arizona, their estimate for all housing is a value premium of about $45,000, while the premium on houses that transact in their sample is closer to $28,000. Wee (2016) finds a similar premium ($35,000) for solar home transactions in Hawai'i, and notes that some of this premium is in part to local grid limits on solar installations and projected energy savings. None of the papers, though, examine if premiums have changed over time.

The majority of research is also focused on homeowner-owned as opposed to non-owned solar. Yet, non-owned solar can still provide benefits to homeowners interested in adopting solar energy—for example for those who are worried about availability of upfront funds and ongoing operating and maintenance (Rai and Sigrin 2013; Rai 2015). Looking more closely at differences in values based on solar ownership structure, Hoen, Rand, and Adomatis (2017) are unable to find similar premiums for non-owned solar panels in their data on housing transactions in California between 2011 and 2013. Our work builds on these earlier findings with a larger dataset that includes both owned and non-owned solar panels, and includes multiple states, and a longer and more recent period.

Many studies explore savings related to energy efficient improvements, but few studies look in detail at solar panel installations and savings. Bardhan et al (2014), discuss the challenges of broad adoption of energy efficient improvements, and show net positive investment returns tied to a variety of energy efficient improvements, specifically citing work by McKinsey (2009) for the nation, and Harcourt, Brown, and Carey (2011), for California. Not all studies are so optimistic though; Allcott and Greenstone (2012) highlight the many challenges researchers face in trying to accurately assess the full costs and benefits of energy efficient improvements and their subsequent savings. Similarly, Borenstein (2012) emphasizes the complexities of accurately pricing solar costs due to different grid pricing, temporal changes, and location. Specifically looking at solar, Adomatis and Hoen (2016) and Hoen et al (2017) both estimate energy costs savings for solar homes across states and find the price increases from solar installations are a conservative estimate of energy savings. Our study also builds on this literature by looking more carefully at the energy savings, installation costs, and premiums in recent years across states.

The closest research to this paper is Hoen et al (2017), which uses CoreLogic tax assessment and deed data from 2002 to 2013 to look at the contribution of solar to property values across covers eight states. That paper finds consistent solar premiums, although they decrease with system age. They also show that the cost of installing solar is a good estimate of these premiums, as is the present value of future savings in some cases. This paper builds on that work by using a more recent time period (2011 through early 2020), and actual appraisal data, rather than assessment data, which have the advantage of providing market valuations, more information on property characteristics, and specific sets of comparable properties for each solar property. This paper also examines energy savings to households and the installed prices of systems, how they have changed over time in relation to premium changes, and some new analyses: appraiser incorporation of energy efficient and solar features, and differences for non-owned solar compared to owned solar.

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[3] Adomatis and Hoen (2016) cover California, Oregon, Florida, Maryland, North Carolina, and Pennsylvania. Hoen et al (2017) covers California, Florida, Maryland, North Carolina, Pennsylvania, Connecticut, Massachusetts, and New York.

3. Institutional Background

Residential Appraisals

The guidelines for residential mortgage appraisals are outlined in the Real Estate Appraisal Reform Act of 1988.[4] The appraisal is to ensure an independent verification of the market value of a property, motivated by concerns that the loan-to-property value ratio is a predictor of default and credit loss (Erkisen et al 2018). Research on home appraisals shows that while appraisers are required to be unbiased, potential anchoring may persist, even after appraisal independence required in the Home Valuation Code of Conduct was codified into Dodd Frank in 2010 (Ding and Nakamura 2016). For example, research shows the high share of appraisal valuations that are equal to or above contract price, and that mortgage insurance loan-to-value thresholds influence valuations (Cho and Megbolugbe 1996; Calem et al 2017; Eriksen et al 2018).

The appraisals we use in this paper were obtained for mortgage lending purposes on purchase transactions. This means a home purchase agreement was in place and the appraiser had the sales contract information in hand. In our sample the appraised value most often matches the sales price (85 percent of the time in our sample they match within zero to five percent above contract price, consistent with Eriksen et al (2018)).

With respect to energy efficiency, Fannie Mae and other institutions (such as the Federal Housing Administration (FHA)) have specific guidelines on incorporating solar panels into appraised value. Fannie Mae requires that appraisers submit an 'adequately supported opinion of market value based on the cost, sales comparison, and income approaches to value, as applicable,' and that all energy-efficient items be mentioned in the official appraisal report (Fannie Mae 2020). Moreover, Fannie Mae states that the contributory value of any energy efficient item should vary based on local climate, utility costs, and overall market demand. Fannie Mae requires appraisers to rely on the market approach to value for all properties including those with solar features, although an appraiser can also consider the cost and income approaches in its analysis.[5] In addition, not all solar panels are able to contribute to housing values. For example, solar panels that are financed as personal property as well as those that are not owned are not allowed to be considered in the property valuation. FHA's guidelines are similar, with some distinctions—for example, they allow the income and cost approaches if there are no comparables available to derive solar value (FHA 2020).

Solar Panels

There are two different forms of solar technology: solar thermal, which uses sunlight to generate heat to create steam to generate energy; and solar photovoltaics (PV), which use sunlight directly converted to electricity via semiconductors. Solar photovoltaics are the subject of our analysis, and are popular because they are adaptable for small-scale uses, such as single-family homes (Borenstein 2012). Solar savings and premiums are often referred to in $/watt because pricing of solar systems is largely based on the size (capacity) of the system (in watts). Watt refers to the capacity of the system, which is measured in direct current (DC) under ideal sunlight and temperature conditions. Over time the physical dimensions of panels have remained fixed, but the efficiency of the panel has increased, which has in turn increased the

[4] https://www.congress.gov/bill/100th-congress/house-bill/3675
[5] See: https://singlefamily.fanniemae.com/media/23956/display

watts/panel. This means the same roof size can produce more energy. This, along with decreasing prices/watt has, in turn, led to increases in system size, because a larger system can fit on the same sized roof.

As energy efficient retrofits gain in popularity, states and localities have established myriad ways to incentivize and regulate residential solar panel installation and use. In many jurisdictions there are regulations or policies governing metering, electricity costs, integration with local grids, permit approvals, and local building codes. In addition, there may be incentives for solar, such as through rebates, tax credits, tax exemptions, performance-based incentives, sellable energy certificates, and other subsidies. California, for example, in addition to requiring solar panels on new construction starting in 2020, also offers incentives like rebates for lower income households, and other local utility incentives.[6] The federal government also offers a tax credit for new solar installation for owned solar. Currently it allows 26 percent of the cost of the system (after state rebates and incentives) to be deducted from taxes; that will lower to 22 percent in 2023, and 10 percent thereafter. The top market for residential solar installations in 2020 was California—a focus of our analysis—followed by Florida and Texas. The other states in our analysis, Connecticut, Massachusetts, and Oregon were ranked 11, 9, and 22 respectively (SEIA 2021).

With respect to purchase and installation, multiple financing arrangements exist for home solar systems, including a cash purchase, homeowner financed, and third-party financed—where the homeowner does not own the system (NHO), but receives financial benefits from it. NHO systems, as a percentage of all systems, peaked in 2012 at 59 percent of the market, but as of 2019 they only represented 37 percent of all installed residential systems (Barbose and Dargouth 2019, 2020).

4. Data Summary

The data we use for our analyses come from a novel dataset combining appraisal data from Fannie Mae's Collateral Underwriter® (CU) database (which collects submissions from the Uniform Collateral Data Portal) and LBNL's Tracking the Sun (TTS) Series, which tracks solar panel installations over time. The appraisal data from CU include purchase loans intended for Fannie Mae, Freddie Mac, and potentially other non-Government-Sponsored Enterprise mortgages, as many financial institutions use the software platform regardless of secondary market intentions (Eriksen et al 2018). The dataset contains standard home characteristics (e.g., square feet of living space, age of the home, parcel size) as well as other non-standard characteristics that are often missing from publicly available datasets (e.g., home condition, construction and neighborhood quality, and energy efficient characteristics such as solar panels). CU coverage is estimated to be about two-thirds of home purchase appraisals (Eriksen et al 2018). The CU data also include analogous information on the comparables that the appraiser selected for each subject property, which we use in our analyses. We exclude sales of brand-new homes from our sample.

LBNL collects the TTS data predominantly from utilities or the state incentive providers.[7] Therefore, the TTS data are both independent of the CU data and are of high quality. The TTS data include the size of

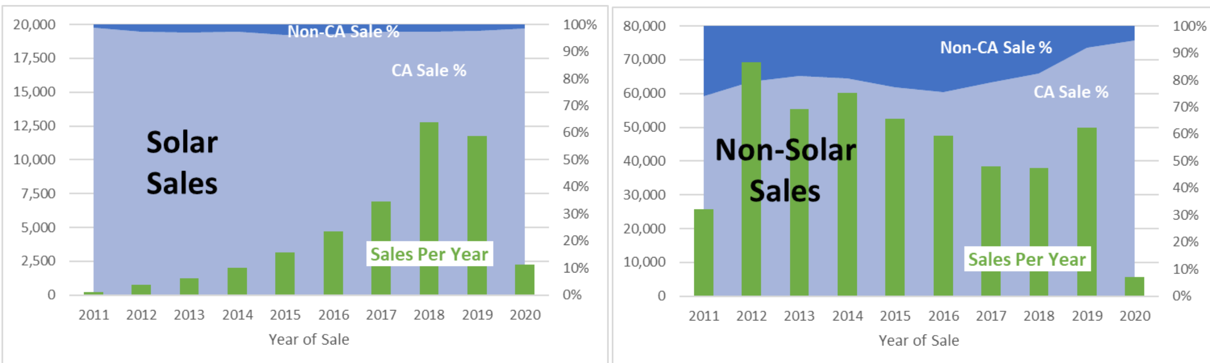
[6] Hughes and Podelesfky (2014) find that upfront rebates have a large effect on solar installations, and they predict close to 58 percent fewer installations would have occurred without California state subsidies. For more information on the subsidies, see: https://www.sunrun.com/solar-by-state/ca/california-solar-incentives.

[7] A minority of the data are collected from permitting jurisdictions and entities that administer solar renewable energy credit (SREC) registration systems or interconnection processes. For more detail on TTS data collection see Barbose and Dargouth (2019).

the solar system, year of installation, and ownership type. Due to data-sharing agreement limitations, we restrict the match to solar panels in CA, CT, MA, and OR. In CA, the shared TTS data are only from three investor-owned utilities, but represent approximately 94 percent of all CA capacity.[8] Overall, these four states comprise more than 48 percent of the total installed U.S. residential capacity (GTM & SEIA 2021).

The final analysis dataset includes 554,947 transactions from 2011 through early 2020, of which about 15 percent are solar homes, approximately eight percent HO and seven percent NHO. Most of the data are from CA (79 percent), and our sample of solar increases with time, as shown in Figure 1, Panels A and B.

Figure 1 (Panel A & B): California Share of Total Solar and Non-Solar Homes by Year

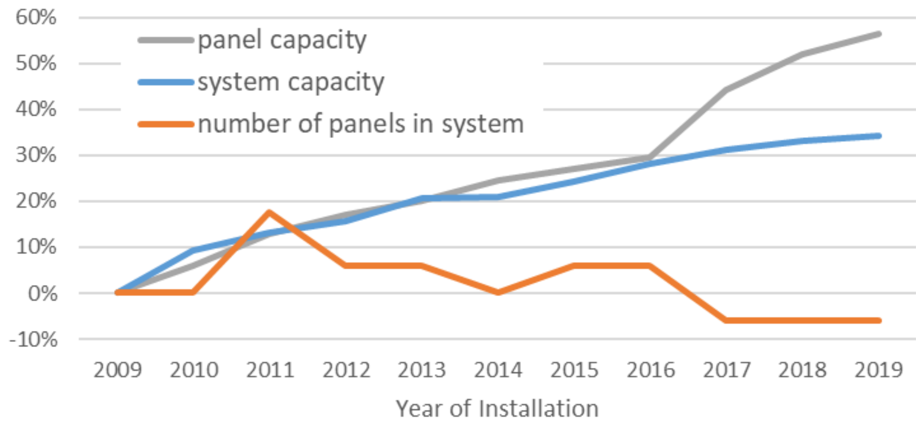


Source: Author calculations from Fannie Mae CU and LBNL TTS merged data. Notes: Panel A (left) represents the solar data contained in the sample, both in terms of total sales per year (primary y-axis) and percent of the sample that are in California or not (secondary y-axis). Panel B (right) describes the non-solar data in the sample. Note that the primary y-axis on Panel A is a different scale than Panel B, and data is only through early 2020.

Summary statistics for the all solar and non-solar homes for our main model specifications are shown in Table 1. The mean contract price of solar homes in nominal dollars is $706,356, slightly higher and statistically different than for non-solar homes at $648,263.[9] However, solar homes are also statistically more like to be larger, newer, outfitted with more bathrooms, and located in California, which likely explains some of the difference in prices. Both groups have similar construction quality and condition at the time of sale. The mean solar system size in our sample is 5.83 kW and it was installed 3.73 years before the sale. As shown in Figure 2 and described in Section 3, although the number of panels in the average U.S. solar system has remained fairly stable over time, the panel capacity has steadily increased, driving up system size. The mean installed cost for the systems in our sample is between $5.2 and $4.8/watt in nominal dollars (or $5.9 and $5.3/watt in 2020 dollars, not shown in table). CA- and non-CA-level summary statistics are provided in Appendix A.

[8] An earlier analysis of these data, using just California, is included in Begley (2018). We also have inconsistent data on Property Assessed Clean Energy (PACE)-financed systems, but we estimate about four percent of our solar panels use PACE financing, all of these properties are in California. Removing them from analysis does not change the results.
[9] The appraisal forms have sales and contract price fields. We rely on the contract price field, as it is the most populated and most likely to be available to appraisers. If contract price is missing, we use sales price.

Figure 2: Percent Change in U.S. Solar Systems and Panels Over Time



Source: Author calculations from Fannie Mae CU and LBNL TTS merged data.
Notes: Although the number of panels in an average sized system has remained fairly stable over time, panel capacity has increased, driving up average system capacity.

Table 1: Summary Statistics for Merged Data, All States and Years

	Non-Solar Homes				**HO Solar Homes**				**NHO Solar Homes**			
variable description	**mean**	**sd**	**min**	**max**	**mean**	**sd**	**min**	**max**	**mean**	**sd**	**min**	**max**
contract price (1,000s of nominal dollars)	648.2	428.3	155.4	3079.0	758.0	462.2	156.0	3075.0	642.1	392.7	155.7	3075.0
natural log of nominal contract price	13.21	0.56	11.95	14.94	13.4	0.54	11.96	14.94	13.23	0.52	11.96	14.94
home has non-homeowner owned (NHO) PV system	n/a				n/a				1.00	0.00	1	1
size of the PV system (kilowatts)	n/a				5.48	2.70	1	15	6.27	2.57	1	15
age of the PV system at the time of sale (years)	n/a				4.1	2.8	0	21	3.3	1.9	0	19
installed cost of the system (nominal $/watt)	n/a				5.2	1.6	1	10	4.8	0.8	3	9
living area (square feet)	2,192	802	937	5,319	2,481	832	940	5,319	2,341	799	937	5,318
natural log of living area	7.63	0.36	6.84	8.58	7.76	0.34	6.85	8.58	7.70	0.34	6.84	8.58
size of parcel (in acres)	0.51	0.95	0.06	9.99	0.57	1.13	0.06	9.98	0.43	0.80	0.06	9.98
percent of first acre	0.34	0.29	0.06	1.00	0.34	0.29	0.06	1.00	0.31	0.26	0.06	1.00
number of acres greater than 1	0.17	0.77	0	8.99	0.23	0.93	0	8.98	0.12	0.64	0	8.98
age of the home at time of sale (years)	37	23	0	114	29	22	0	114	30	21	0	114
number of half bathrooms	0.37	0.53	0	5.00	0.38	0.51	0	5	0.34	0.49	0	5
number of full bathrooms	2.29	0.76	1	8	2.55	0.76	1	7	2.43	0.74	1	6
number of bedrooms	3.61	0.78	0	10	3.79	0.80	1	10	3.76	0.81	1	9
the home has energy efficient features	0.22	0.42	0	1	0.26	0.44	0	1	0.25	0.43	0	1
number of garage spaces	2.18	0.77	0	9	2.39	0.72	0	9	2.36	0.71	0	9
up to or less than 3 garage spaces	2.13	0.64	0	3	2.33	0.57	0	3	2.31	0.58	0	3
any additional garage spaces > 3	0.05	0.32	0	6	0.06	0.33	0	6	0.05	0.31	0	6
condition of the home at the time of sale	3.10	0.56	2	5	2.97	0.50	2	5	3.03	0.50	2	5
relatively new or recently renovated (2)	0.11	n/a	0	1	0.14	n/a	0	1	0.11	n/a	0	1
well maintained (3)	0.69	n/a	0	1	0.74	n/a	0	1	0.75	n/a	0	1
minimal repairs (4)	0.20	n/a	0	1	0.11	n/a	0	1	0.14	n/a	0	1
significant repairs (5)	0.004	n/a	0	1	0.000	n/a	0	1	0.000	n/a	0	1
quality of construction	3.56	0.57	2	5	3.49	0.58	2	5	3.58	0.54	2	5
custom designed (1)	0.03	n/a	0	1	0.04	n/a	0	1	0.02	n/a	0	1
high-quality above standard (2)	0.38	n/a	0	1	0.42	n/a	0	1	0.38	n/a	0	1
meet or exceeds codes (3)	0.58	n/a	0	1	0.52	n/a	0	1	0.60	n/a	0	1
basic economy (4)	0.006	n/a	0	1	0.002	n/a	0	1	0.001	n/a	0	1
view from the home	1.19	0.40	1	3	1.22	0.42	1	3	1.16	0.37	1	3
beneficial (2)	0.19	n/a	0	1	0.22	n/a	0	1	0.16	n/a	0	1
neutral (1)	0.81	n/a	0	1	0.77	n/a	0	1	0.84	n/a	0	1
adverse (3)	0.002	n/a	0	1	0.001	n/a	0	1	0.001	n/a	0	1
neighborhood description	1.25	0.60	1	3	1.23	0.58	1	3	1.22	0.58	1	3
beneficial (2)	0.08	n/a	0	1	0.22	n/a	0	1	0.06	n/a	0	1
neutral (1)	0.84	n/a	0	1	0.77	n/a	0	1	0.86	n/a	0	1
adverse (3)	0.09	n/a	0	1	0.001	n/a	0	1	0.08	n/a	0	1
n	**471,204**				**46,486**				**37,257**			

Source: Author calculations from Fannie Mae CU and TTS merged data, 2011 through early 2020.

5. Methodological Approach

5.1 Base Models

To examine the influence of solar panels on housing values, we use hedonic price models, similar to the comparable sales method on which most appraisals rely. With our sample of appraised sales and their comparables, we estimate the additional value of solar relative to comparable non-solar homes.[10] The basic theory behind the hedonic pricing model starts with the concept that a house can be thought of as a bundle of characteristics. When a price is agreed upon between a buyer and seller, there is an implicit understanding that those characteristics have value. The average marginal contribution of each

[10] For most appraisals, the practitioner would seek to collect a few solar homes that have sold and compare them to a few non-solar homes to establish the contributory value of solar, also known as the 'paired sales' approach.

characteristic to the contract price can be estimated with a hedonic regression model (Rosen, 1974; Freeman, 1979; Sirmans et al., 2005). Equation (1) reflects our main hedonic specification:

*ln(price) = f(parcel*CA*year, structure*CA*year, solar panel presence, energy efficient features*CA*year, neighborhood*CA*year, sale quarter FEs, state*year FEs, ZIP code FEs)* (1)

Our preferred model uses a relatively simple set of home and site characteristics, displayed in Table 1: the natural log of the contract price for the home; the unit size (natural logged square feet of living area); the unit age at sale (years); age of the home squared; the size of the parcel (acres); the number of garage spaces;[11] the number of full and half bathrooms; the number of bedrooms; home condition; view; and construction and neighborhood quality. It also includes the presence and size of the solar systems, as well as a flag for other energy efficient features as noted by the appraiser. To additionally control for neighborhood characteristics, we include ZIP code fixed effects, which, in all cases, includes at least five solar homes and 15 non-solar homes.[12] Broader market factors are accounted for by including dummy variables for the sales quarter. Additionally, to capture unique macroeconomic conditions, housing price trajectories, and amenity variation across time and space, and given California's unique position in the solar market, we include a California-by-year fixed effect interaction interacted with each of the housing and neighborhood characteristics noted above. This model form was chosen for its relative parsimony, its high adjusted R^2, and its flexibility to estimate state- and year-level solar home effects with only an interaction of the solar variable.[13].

The primary parameter estimate of interest in this model (Model 1) is *solar panel presence*, which represents approximately the marginal percentage change in contract price due to the presence of solar, relative to the average contract price of the set of homes within the same ZIP code and sale quarter, and relative to California in a given year.[14]

In addition to Model 1, we also include a model investigating the relationship between the solar panel ownership structure, comparing owned and non-owned panels (Model 2). Even though they are not allowed to be included in the appraised value of the home, non-owned panels may be attractive to homeowners because they are may lower overall energy costs, and they may provide positive green signals to others.

The size (capacity to produce energy) of the solar system can vary substantially between homes based on their annual energy usage and available roof space. Because larger systems have larger costs and

[11] Acres and garages are entered into the model as spline functions using two variables for both to capture the diminishing returns of adding additional acres and garages. For acres, the spline occurs for acres greater than 1, and for garages, the spline is located at more than 3 garages. Additionally, square feet and age squared are entered into the model in 1,000s to allow for easier interpretation of the coefficients.

[12] A normal ZIP code contains between 100 to 13,000 homes (10^{th} & 90^{th} deciles) with a median of 1,300 (based on ZCTA counts from the 2019 5-year American Community Survey). By including this fixed effect, and requiring each to contain at least five solar and 15 non-solar homes, the solar estimates are a comparison of those two home types within the ZIP code, while controlling for temporal and characteristic differences between them. We also examined using higher numbers of transactions within each ZIP code, and instead using the county as a fixed effect, which only resulted in small changes to the variables of interest.

[13] Model choice for this work was informed by findings from previous analyses (Hoen et al., 2011; 2013a; b). In models not shown, we also tried different versions of controls for time and space with similar results: for example, using a combined sale year and quarter fixed effect, and not interacting sale year and CA with other covariates. The Stata command "reghdfe" was used to accommodate the multiple fixed effects and error clustering efficiently (Correia, 2014 ; Guimaraes & Portugal, 2010).

[14] To be exact, the conversion to percent is EXP(β)-1, the marginal percentage change is a close approximation.

potential savings, one would expect the market to be willing to pay more for those systems. To investigate this relationship, we estimate a model including the size of the solar system as a continuous variable for owned-solar homes only, compared to non-solar homes in the same ZIP code (Model 3).[15, 16]

5.2 Additional Samples and Specifications

Model 3 is our preferred specification and sample, so we further explore that relationship in two additional models. First, we look at how the relationship between solar and housing values varies across states by adding an interaction with solar system size for California and our non-California states. This allows us to more cleanly capture differences in solar values across different state markets and institutional contexts (Model 4). Then, we estimate a model with an solar system size interaction with year to isolate the differences in premiums over time, as solar installation and energy costs have changed (Model 5). We look at the relationship individually by year to account for decreasing solar installation costs and increasing electricity prices over time—over our sample period, average residential electricity rates increased by 10 to 50 percent. (Barbose & Dargouth, 2020). The complete list of our models is outlined in Table 2.

Table 2: Model Summaries

Model	Variable of Interest (β_4)	PV Home Sample	Model Description
1	PV_i	Full Sample: Homes with both homeowner owned (HO) and non-homeowner owned (NHO) solar PV systems	Estimate effects for all solar homes together
2	PV_i*NHO_i	Full Sample	Estimate effects separately for HO and NHO solar homes
3	PV_i*$SIZE_i$	Homes with HO systems	Estimate effects for just HO solar homes based on the size of the PV systems
4	PV_i*$SIZE_i$ for CA_i	Homes with HO systems parsed by CA or not CA	Same as Model 3, but estimate effects for CA and non-CA homes separately
5	PV_i*$SIZE_i$ for each $YEAR_i$	Homes with HO systems parsed by year of sale	Same as Model 3, but estimate effects foreach year separately

5.3 Replacement Cost and Net Energy Savings Estimates

In many real estate markets, either there are too few sales to reliably conduct a comparable sales analysis for a solar home, or the information on the solar system is absent from the data. As noted earlier, in some cases an appraiser may also incorporate an estimate of the solar panel replacement cost or the present value of a stream of energy savings from the solar unit (the income approach) into its valuation.

[15] Size of the system is reported in direct-current watts or kilowatts under standard test conditions, as described in Appendix A of Barbose et al. (2019).

[16] Additionally, we estimated two models, one with only solar homes to examine if contract prices are correlated with the size of the system in that sub sample, and one with only homes that sold before and after solar system installation (repeat sales). We find strong statistically significant relationships in both cases between contract price and increasing solar system size. We believe, though, that without the comparison to comparable non-solar homes, for the first model, and with the paucity of data available for the second, the estimate is less meaningful and therefore we do not include here. Those results are available upon request from the authors.

Therefore, these alternate estimates are non-trivial, and we calculate both income and replacement cost values for each sold solar system in our sample to compare with our hedonic pricing model estimates.

5.3.1 Replacement Cost Estimates

The replacement cost estimate is derived from the gross installation costs available to LBNL in their full TTS database, which is then incorporated into a statistical model that uses housing and solar unit characteristics, local costs, and other local and federal incentives. The procedure is detailed in Appendix B and results in an estimate of both gross and net (net of federal and state incentives) installation costs for each solar panel system in our data. The average real (2020 $s) gross and net replacement costs for the systems in our HO solar sample are $4.36/ watt and $2.86/watt respectively, which for a 5 kW solar system translate into respective values of $20,907 and $14,025 (Table 3).[17]

5.3.2 Income Estimates

For each solar home in our sample, we received an estimate of the present value of energy bill savings over 20 years from the energy consulting firm Clearly Energy. Clearly Energy uses the size and age of the system, the ZIP code of the home, and the estimated tilt and azimuth of the system[18] fed through an algorithm to produce estimates for utility bill savings for a similarly sized system as of the time of sale.[19]

The algorithm is outlined by Klise and Johnson (2012), and the inputs for our current research effort are based on the following: the expected energy output of the solar system after the sale date and assuming a life span not greater than a conservative 20-year warranty life for the panels; an electricity retail rate at the time of sale, and an escalation of the rate similar to the historical escalation over the previous 10 years from the U.S. Energy Information Administration, Form 861 public data; discount rates as of the time of sale equivalent to 125 basis points above the 30-year, fixed mortgage rate from the Freddie Mac Primary Mortgage Market Survey; a system direct current-to-alternating current derate factor of 86 percent; a module degradation factor of 0.6 to 1.0 percent per year; and an expected inverter replacement at 10 years. Tiered rates, which are prevalent in California, are not used, but instead an average ZIP code-level rate is approximated and weighted averages are calculated when multiple utilities are present in a ZIP code (tiered rates are generally higher than average rates, so this may understate our estimates of savings). The average real (2020 $s) present value of energy savings for the systems in our HO solar sample is $3.37/watt, which for a 5 kW solar system, translates into $16,227 (Table 3).

[17] Note NHO solar installed costs, which are often derived from vertically integrated solar companies, are difficult to obtain and not well trusted when they are. Therefore, only the owned-solar costs are presented. Additionally, it is reasonable that the replacement cost values should be depreciated (via straight-line over 20 years, the term of a normal solar system warranty), but we only present the undepreciated values here.

[18] Tilt and azimuth were available for most solar systems. When they were not, they were estimated via a cascading approach based on median values of systems in the same census block group; if that estimate was not available, then we used the median value in the census tract or finally, in the county.

[19] The estimation procedure produces a set of low, average, and high estimates of the present value of the expected energy output, based on a risk premium of 50, 100, and 200 basis points, respectively. Only the average value was used for this analysis.

Table 3: Average Gross and Net Replacement Costs and Energy Savings Estimates for HO Systems (Nominal and Real 2020 $s), 2011 through early 2020

	Solar Home Transactions (HO Only)				
description	**mean**	**sd**	**min**	**max**	**Estimate in $ for 5 kW Solar System**
gross solar system replacement cost at the time of sale (nominal $/watt)	$ 4.18	$ 0.46	$ 2.72	$ 7.30	$ 20,907
net solar system replacement cost at the time of sale (nominal $/watt)	$ 2.81	$ 0.39	$ 0.20	$ 4.59	$ 14,025
present value of energy savings at the time of sale (nominal $/watt)	$ 3.25	$ 0.93	$ (0.04)	$ 6.19	$ 16,227
gross solar system replacement cost at the time of sale (2020 $/watt)	$ 4.36	$ 0.59	$ 2.65	$ 8.33	$ 21,801
net solar system replacement cost at the time of sale (2020 $/watt)	$ 2.86	$ 0.45	$ 0.03	$ 5.11	$ 14,294
present value of energy savings at the time of sale (2020 $/watt)	$ 3.37	$ 0.94	$ (0.04)	$ 6.18	$ 16,833

Source: Author calculations from LBNL data. Net costs are calculated using gross costs net of federal and state incentives.

5.4 Solar Home Flagging

An open question for researchers is the extent to which appraisers note the presence of solar in their appraisal valuations. The CU dataset contains an open text field that captures energy efficient characteristics of the home, but there is no specific box that appraisers check to indicate the presence of solar panels. If solar was flagged by the appraiser as being worthy of note for the sales comparables approach, it would be captured in this field. Using a combination of standard search terms and manually parsing, a full set of over 9,000 unique strings were recoded into four variables.

1. Solar Flag: The appraiser noted the home had a solar system—on average, 65 percent of the HO solar sales were flagged as having solar by the appraiser and 43 percent of the NHO sales.
2. Non-Homeowner Owned Solar Flag: The appraiser noted that the home had solar and that the solar system was leased or under a power purchase agreement, and therefore owned by a third party and not the homeowner—19 percent of the NHO systems were flagged as such by the appraiser, though as noted above a higher percentage were at least flagged as solar.
3. Homeowner-Owned Solar Flag: The appraiser noted that the home had solar and that the solar system was owned by the homeowner—20 percent of the HO systems were flagged as such by the appraiser, and as noted above a higher percentage were at least flagged as solar.
4. Energy Efficient Items Flag: The appraiser noted other energy efficient features, including insulation or multi-pane windows. A property can be flagged for having energy efficient items with or without solar—25 percent of solar homes are flagged for energy efficient items and 22 percent of non-solar homes, a statistically significant difference.

These fields provide a few novel analysis options. First, we were able to identify if appraisers correctly noted if the home had solar at the time of sale using the TTS information. Second, we can identify the frequency of noting solar ownership structure. Finally, including energy efficient features allows us to control for the additional amenity effect of those features on housing values in our models.

6. Results

6.1 Base Model Results

The variable of interest results from Models 1, 2, and 3 shown in Table 4. The first column shows that the presence of solar panels is correlated with a housing price increase of about 0.87 percent over the average price of similar homes in a given ZIP code, state (CA or not), sales quarter, and year. Column 2 explores this relationship further, splitting solar into owned and non-owned systems. Here, we see the relationship between solar panels and housing prices is entirely driven by owned solar panels, with a price increase of 1.63 percent. In contrast, the relationship between non-owned solar and housing prices is negative, very small, and not statistically significant. Figure 3 visualizes this relationship, comparing the owned and non-owned premiums. However, as mentioned earlier, the relationship between solar panels and housing prices alone is less meaningful than the role of house prices and the size of the solar system.

We explore solar size in column 3, which includes the interaction of solar panel presence and solar panel size only for owned solar systems. This model shows that a one kilowatt increase in installed capacity of a homeowner-owned solar system is correlated with a 0.40 percent increase in sales price, which translates to a premium of approximately $14,500 for an average sized system of 5.5kW, or $2.66/W.

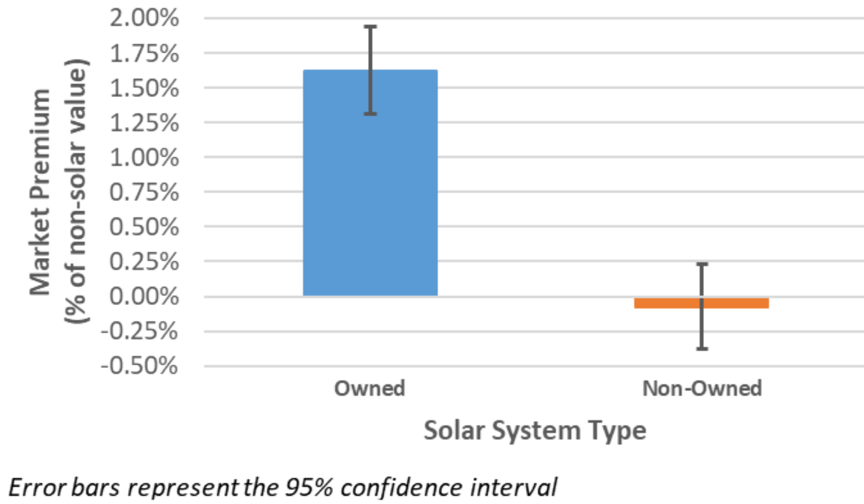
Although not shown, other covariates have the expected signs and levels and are fairly consistent over time and space across these models.

Table 4: Results from Hedonic Models

Model	(1)	(2)	(3)
Variable	**Coefficient (SE)**	**Coefficient (SE)**	**Coefficient (SE)**
home has a solar photovoltaic (PV) system	0.0086***		
	(0.0011)		
home has a homeowner owned (HO) PV system		0.0161***	
		(0.0016)	
home has a non-homeowner owned (NHO) PV system		-0.0007	
		(0.0016)	
size of the HO PV system (kilowatts)			0.00399***
			(0.0002)
California * Year Interacted Covariates	Yes	Yes	Yes
ZIP Code Fixed Effects *n*	1,384	1,384	1,253
Sample and Results Summary			
Total *n*	554,947	554,947	488,356
PV *n*	83,743	83,743	45,840
Non-PV *n*	471,204	471,204	442,516
Adjusted R^2	0.94	0.94	0.94
Within ZIP Adjusted R^2	0.73	0.73	0.73
Dependent Variable	lnspn	lnspn	lnspn

Notes: Results from hedonic models as specified in equation (2). Models include all covariates and ZIP code fixed effects and clustered standard errors, and CA x year interactions with sale quarter, parcel, structure, and neighborhood characteristics. Garage and acreage enter the regression as splines. ***$\rho <$ 0.001, ** $\rho < 0.01$, * $\rho < 0.05$.

Figure 3: Comparing Premiums for Homeowner-Owned and Non-Owned Solar Panels



Source: Author calculations from Fannie Mae CU and TTS merged data.
Notes: Model results displayed in Table 4. Homeowner-owned panels are statistically significant at $\rho <$ 0.001; non-homeowner-owned panels are not statistically significant.

6.2 Additional Results

Next, we further explore our preferred specification of solar panel size in kilowatts for homeowner-owned solar panels. We add an interaction to our model to estimate the solar panel size by state (Model 4) and solar panel size by year (Model 5), which allows for differential effects across time and space in our sample.

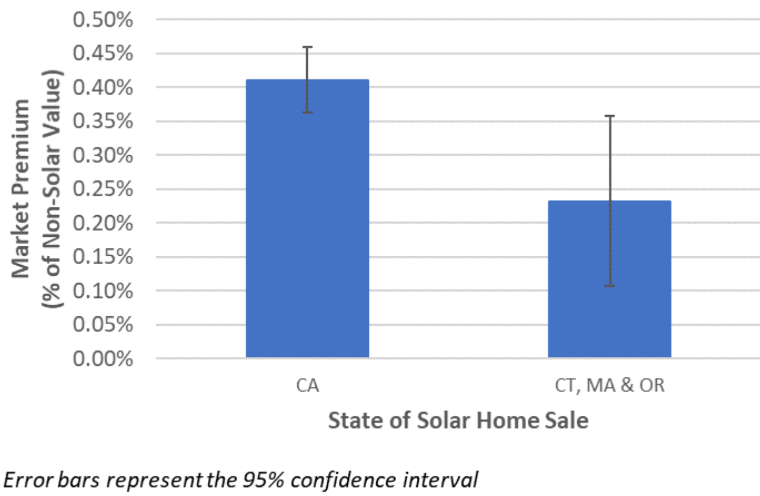
Table 5: Results for Hedonic Models by State and Year

Model	(3)	(4)	(5)	(6)
Label	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)
size of the HO PV system (kilowatts)	0.00399***			0.009***
	(0.00024)			
size of the HO PV system (kilowatts)				
sold in CA		0.0041***		
		(0.00025)		
sold in CT, MA or OR		0.0023***		
		(0.00064)		
size of the HO PV system (kilowatts)				
sold in 2011			0.0118***	
			(0.00327)	
sold in 2012			0.0073***	
			(0.00168)	
sold in 2013			0.0063***	
			(0.0012)	
sold in 2014			0.0065***	
			(0.00103)	
sold in 2015			0.0062***	
			(0.00066)	
sold in 2016			0.0043***	
			(0.00046)	
sold in 2017			0.0035***	
			(0.00039)	
sold in 2018			0.0033***	
			(0.00032)	
sold in 2019			0.0035***	
			(0.0003)	
sold in 2020			0.0039***	
			(0.00061)	
California * Year Interacted Covariates	Yes	Yes	Yes	Yes
ZIP Code Fixed Effects *n*	1,253	1,253	1,253	554
Results Summary				
Total *n*	488,356	488,356	488,356	6,246
PV *n*	45,840	45,840	45,840	3,436
Non-PV *n*	442,516	442,516	442,516	2,810
Adjusted R^2	0.94	0.94	0.94	0.92
Within ZIP Adjusted R^2	0.73	0.73	0.73	0.64
Dependent Variable	lnspn	lnspn	lnspn	lnspn

Notes: The Models are described in more detail in Table 2. Model 3 repeats the result from Table 3 for reference. Model 4 shows the analogous results parsed by CA or non-CA and Model 5 shows the analogous results parsed by year. All models include ZIP code fixed effects and clustered standard errors, and CA x year interactions with sale quarter, parcel, structure, and neighborhood characteristics. Garage and acreage enter the regression as splines. ***$\rho < 0.001$, ** $\rho < 0.01$, * $\rho < 0.05$.

The third column in Table 5 shows the coefficients for solar panel size in the hedonic models separating out California. Clear differences arise across the models: the premium for CA is similar to the full sample, with a one kilowatt increase in installed capacity correlated with a 0.41 percent increase in price. In contrast, the combined premium for Connecticut, Massachusetts, and Oregon is lower at 0.23 percent (Figure 4).

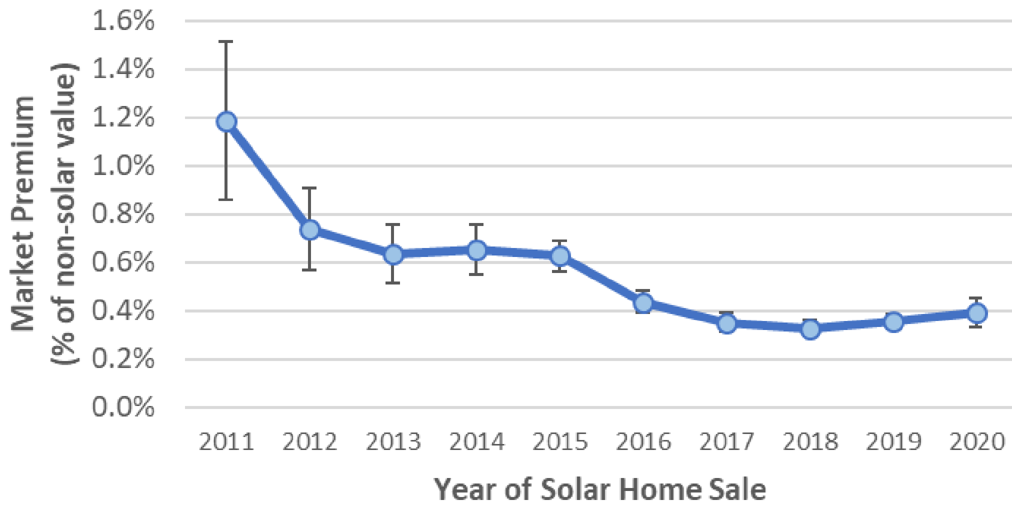
Figure 4: Homeowner-Owned Solar Panel Premiums Compared to Non-Solar Homes, by State



Source: Author calculations from Fannie Mae CU and TTS merged data.
Notes: Model results displayed in Table 5. California is statistically significant at $\rho < 0.001$, as is the pooled effect of Connecticut, Massachusetts, and Oregon.

The coefficients on solar panel size results by year (Model 5) are shown in column four, and show a clear pattern of declining solar premiums over time. For example, in 2011, a one kilowatt increase in installed capacity for a homeowner-owned solar system was correlated with a 1.23 percent increase in sales price. In the years after 2016, this premium is reduced to below 0.4 percent (Figure 5), which is a highly statistically significant difference (p <0.000). We explore this decreasing trend further in the next section when we also calculate changes in solar replacement costs and energy savings over time.

Figure 5: Homeowner-Owned Solar Panel Premiums Compared to Non-Solar Homes, by Year



Error bars represent the 95% confidence interval

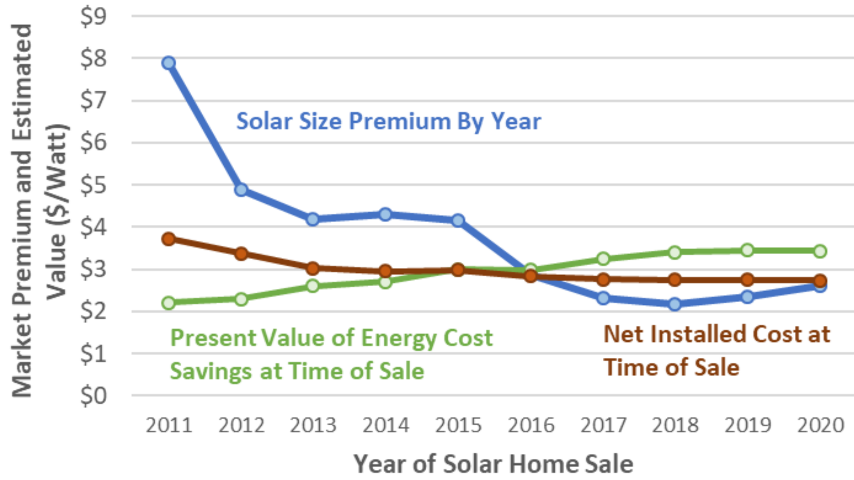
Source: Author calculations from Fannie Mae CU and TTS merged data.
Notes: Model results displayed in Table 4. All coefficients are statistically significant at $\rho < 0.001$.

6.2 Replacement Costs and Energy Savings

Now, we turn to the replacement cost and energy savings calculations for our samples by year and state. For each property with solar, we calculate the net replacement costs and projected energy savings at the time of property sale, as discussed earlier. These values are presented in $ per installed watt. Similarly, we convert the solar coefficients presented in Table 5 in percentages to $/watt.[20] Figure 6 displays our results comparing the replacement cost, energy savings, and hedonic solar size premiums in $/watts by year.

[20] This conversion is done as follows: (EXP(β)-1)*nominal contract price of non-solar homes. Models 3-5 use the same non-solar home contract price of $661,696. This amount is slightly different than what is shown in Table 1, which includes non-solar homes in ZIP codes with both HO and NHO solar.

Figure 6: Solar Home Premium, Installed Costs and Present Value of Energy Savings by Year, $/watt

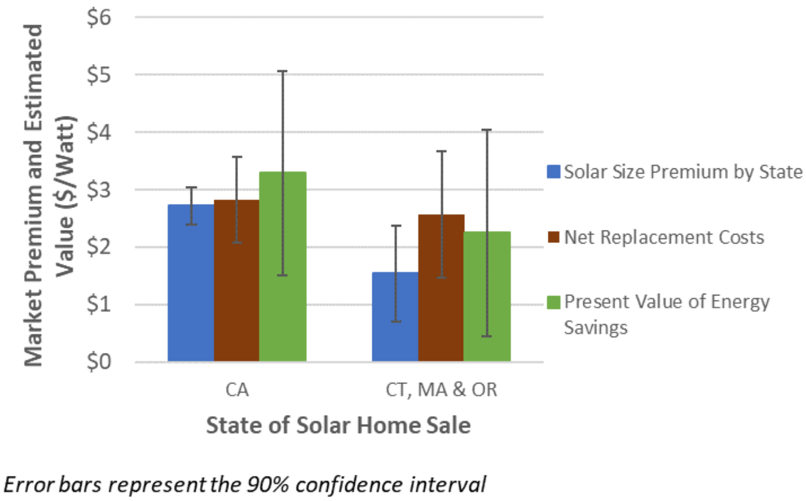


Source: Author calculations from Fannie Mae CU and TTS merged data.
Notes: Model results for solar panel premiums displayed in Table 5 and converted to $/watt. The present value of energy cost savings and the net replacement costs are calculated at the time of property sale and described in Section 5.

The trends displayed in Figure 6 show a convergence in the three metrics over time. Solar premiums have been declining, energy savings have been increasing, and net replacement costs have dropped slightly over time. This convergence of market premiums to the cost and income market signals may reflect solar panel adoption becoming more common, and thus the original new, early adapter, or novelty signal premiums of solar panels declining. Now the premium more closely reflects the cost of installing the unit and its potential energy savings.

Figure 7 shows the analogous comparison of premiums, net replacement costs, and the present value of energy savings for each solar property, based on our state analyses. Across the two state samples, the solar premium is not statistically different from those of the replacement costs or projected savings.

Figure 7: Solar Home Premiums, Installed Costs, and Present Value of Energy Savings by State, $/watt



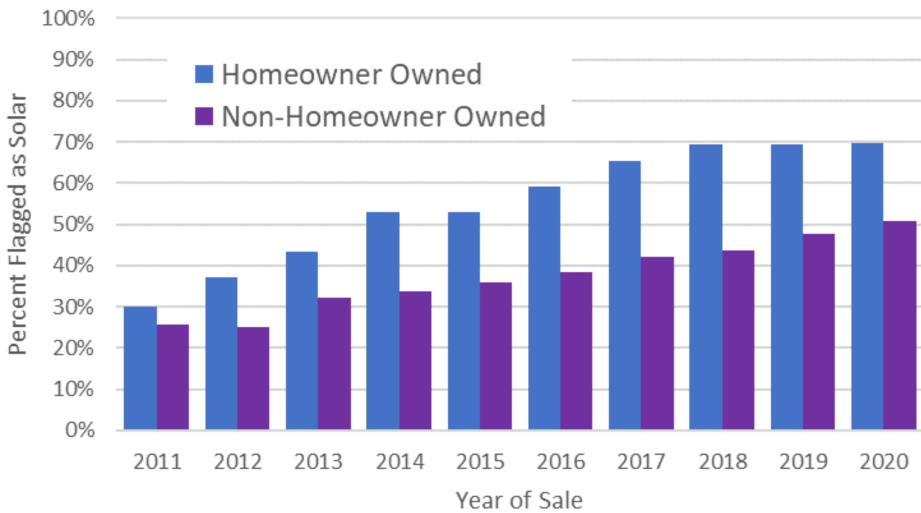
Source: Author calculations from Fannie Mae CU and TTS merged data.
Notes: Model results for solar panel premiums displayed in Table 5 and converted to $/watt. The present value of energy cost savings and the net replacement costs are calculated at the time of property sale and described in Section 5.

6.3 Solar Home Flagging

Finally, we present how often solar homes were flagged by appraisers. Overall, the share of solar homes that are correctly identified as solar has increased over time, from only 29 percent in 2011 to 62 percent in 2020. Moreover, solar panels are much more likely to be correctly identified in homeowner-owned panels, with about 70 percent of solar panels flagged in the appraisal on average since 2018 (Figure 8). Alternatively, for non-homeowner owned systems, appraiser flagging only just reached 50 percent in early 2020.[21]

[21] Although not investigated further here, it would be valuable to understand how often, in addition to flagging the system, the appraiser incorrectly identified the system as HO or NHO.

Figure 8: Share of Solar Homes Correctly Flagged in Appraisals



Source: Author calculations from Fannie Mae CU and TTS merged data.

In addition to sales prices and solar flags, we collected data on the appraised housing value, if available within the CU database. We find appraised values of appraiser-identified solar homes, after controlling for other aspects of the home via the regression model as described in equation (2), are significantly higher than non-solar homes (β=0.020, p<0.000). Similarly, higher appraised values are significantly correlated with larger sized solar systems (β=0.017, p<0.000), which is very similar to our estimate using contract prices as the dependent variable. This indicates that appraisers, despite not flagging all solar homes, add value to those homes that they do flag at appropriate levels.[22] The fact that our appraised-value solar premium is close to our contract price premium estimate is not surprising, given that almost 85 percent of appraised values are within zero to five percent of contract prices in our data.

7. Discussion

This analysis uses a unique dataset of solar panels and housing prices, which the authors believe is unparalleled for its size and quality. It provides an opportunity to look at the influence of solar systems on home values at a higher resolution than was previously possible. Using these data, we examine if premiums exist across four states for solar system installations from 2011 through early 2020. We find clear evidence that solar homes are indeed selling for higher values than non-solar homes, with a premium of almost one percent. Incorporating panel size into our models provides a premium of approximately $2.66/watt or $14,500 for an average sized system of 5.5kW. This is well below estimates

[22] Interestingly, appraiser solar flagged homes that are also flagged as NHO solar have statistically significantly lower appraised values, while the same is not true for HO flagged solar. This might indicate appraisers are discounting appraised values for NHO solar systems they identify as such, or that they are attributing another property feature to the discounted value, as described in Eriksen et al (2018). Further study is needed to better understand these relationships.

from prior studies. Hoen et al. (2017), and Adomatis and Hoen (2016), both estimated the premium for solar homes in their samples at approximately $4.25/W, though they used data from an earlier period.

We find a more nuanced story when we divide the data into subsets, which helps explain the differences with previous studies. Since 2011, we estimate premiums have dropped by almost $6/W, losing more than 75 percent of system value through 2020. This drop aligns with the decrease in installed prices of solar systems over this period; however, our estimates of solar home premiums dropped faster than net installation costs. We do not observe the same correlation with the trend in the energy savings estimates at the time of sale. In fact, as solar premiums decreased over the sample period, projected energy savings increased due to steadily increasing utility rates. Nevertheless, since 2016, premiums have been within approximately $1/watt of both the present value of energy savings and the net replacement cost.

The drop in solar home premiums might be due to the move of solar from an early to late adopter phase. Buyers of homes with solar are adopting the technology later than the selling homeowner; however, broader solar saliency might provide market signals to the buyer too. Palm (2020) describes early adopters as driven by "environmental concern and technophilia," and later adopters as more focused on economics. This builds on the seminal work of Rogers (1962) who classifies the early adopters as being less likely to be financially risk-adverse because they are wealthier than later adopters. O'Shaughnessy et al (2020) find that more recent solar adopters are indeed less wealthy than their predecessors.

We also find that system sizes increased as installed prices decreased, indicating greater commoditization of the product. The fact that energy savings are outpacing replacement costs and premiums suggests buyers are also less attentive to the energy saving characteristics of solar, as Houde (2018) and Sussman (2020) found. These are all aligned with Bruegge et al (2016) (mentioned earlier), who find that changing consumer mix, marketing, housing stock filtering, stricter building codes, and broader macroeconomic forces may all explain some of the decline in value for Energy Star-rated homes over time. Overall, the replacement cost decline over time seems to be a stronger market signal than the increasing energy cost savings. In summary, the decline in value of solar homes over time might be an indication of market maturation, both in terms of the cost of the technology and the adopters that are installing and buying homes with it. Although this might mean less value for sellers of solar homes, it also connotes that solar is faring better in the broader market as more and more adopters accumulate.

We also found that non-homeowner owned systems do not garner any noticeable premium. This is not surprising for a number of reasons. First, these systems are not considered real property. Therefore, our dependent variable—home selling prices—should not contain a premium. The cost savings from a non-owned system are often trivial because they are largely offset by a lease or power purchase payment. Further, given the adopter changes noted above, these savings are likely not priced into the selling price. Non-owned solar transfers to the home buyer also come with additional paperwork. Although this might not be onerous, it is one additional administrative cost in the sales process, which might lower any inherent value. Regardless of the reasons, we find no evidence of increased values for homes with non-owned solar systems.

Finally, we investigated if appraisals are regularly noting solar as an energy efficient property feature. We find this to be occurring with greater frequency each year, and more often for homeowner-owned systems. Additionally, we find appraised values for homes flagged by appraisers to be higher, indicating that they are, to some degree, mimicking the market. This is aligned with the other research on appraisals that shows that appraised values most often match contract prices.

While our results add to the literature on the role of solar panels in the housing market, there are two caveats to our findings. First, we cannot fully control for selection bias among solar panel homeowners.

While we have an abundance of housing and neighborhood attributes in our data, we do not have information about solar homebuyers, and therefore some of our premium may be attributed to specific types of homeowners who are wealthier and/or will pay a premium for a solar home due to higher expected energy usage or perceived benefits (as noted in Rai and McAndrews (2012), Borenstein (2015), and Bruegge et al (2018)). Second, while we control for many property and neighborhood-level factors in our analyses—and our use of comparable properties helps ensure that our non-solar sample is similar to our solar sample, there is still the possibility that solar panel homes are different than other properties in ways that will increase value and for which we cannot measure or control with our data. Ultimately, we cannot claim that our estimates are causal.

Nevertheless, our findings are robust to many controls and specifications, and suggest that real estate practitioners should redouble their efforts to ensure that solar is regularly identified and properly valued at the time of sale. And, importantly, that those values are not overly inflated beyond the replacement cost and present value of energy savings estimates, which appear to be strong market signals. This is especially true given the increased emphasis on solar from the new administration and state-level renewable energy goals.

This work offers a number of additional areas of future study, including: investigating solar premiums across homes of different values, especially in low- and moderate-income communities where solar might offer an important wealth creation or savings opportunity; estimating the effect on new homes, especially those in CA after the Solar Home Mandate now requires most new homes to have solar; exploring appraiser practices, such as how often appraisers determine if comparable homes have solar or not or how often appraisals incorporate replacement and income approaches when valuing solar; and, researching the strength of the relationship between the age of the solar system and its premium.

8. Conclusions

The residential solar market is growing rapidly, with increasing solar installations and solar home resales. Past research has found relatively high premiums for homes with homeowner-owned solar systems compared to current solar installation costs. In this paper, we explore how current premiums have changed over time, particularly in relation to changes in replacement costs and energy savings. We also explore whether the solar panel ownership structure affects solar premiums, and whether appraisals accurately identify solar panels. Our large dataset combining Fannie Mae appraisal data with Lawrence Berkeley National Lab solar data allows us to answer these questions in more detail and with better granularity than past studies.

We find clear evidence that solar systems are correlated with higher selling prices if those systems are owned by the homeowner (HO). Alternatively, we find no value or slightly lower values associated with non-owned panels. Our estimates show premiums for HO systems have dropped over our study period in the four states we analyze, which is correlated with a decreasing replacement costs for similarly sized systems and the overall maturation of the solar market. Notably, as energy costs increase, calculations of projected savings from solar panels now surpass our replacement cost and estimated value premium calculations. Finally, we find that appraisals are more regularly flagging solar on homes today, but rarely do they provide information on panel ownership structure. We rely primarily on contract prices in our models, but see similar value premiums when using appraised values in place of contract prices in our analyses.

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9. Appendix A: State-Level Summary Statistics

Table A1: California Sample Summary Statistics

	Non-Solar Home Transactions				Solar Home Transactions			
description	**mean**	**sd**	**min**	**max**	**mean**	**sd**	**min**	**max**
contract price (1,000s of nominal dollars)	$ 713	$ 453	$ 155	$ 3,079	$ 772	$ 468	$ 156	$ 3,075
natural log of nominal contract price	13.31	0.56	11.95	14.94	13.40	0.54	11.96	14.94
home has non-homeowner owned (NHO) PV system	n/a				0.00	0.00	0	0
size of the PV system (kilowatts)	n/a				5.44	2.70	1	15
age of the PV system at the time of sale (years)	n/a				4.10	2.87	0	20
installed cost of the system (nominal $/watt)	n/a				5.20	1.62	1	10
living area (square feet)	2,254	804	937	5,319	2,503	829	940	5,319
natural log of living area	7.66	0.35	6.84	8.58	7.77	0.33	6.85	8.58
size of parcel (in acres)	0.44	0.91	0.06	9.99	0.55	1.11	0.06	9.98
percent of first acre	0.29	0.26	0.06	1.00	0.33	0.29	0.06	1.00
number of acres greater than 1	0.15	0.74	0	8.99	0.23	0.91	0	8.98
age of the home at time of sale (years)	35.66	21.67	0	114.00	28	21	0	114
number of half bathrooms	0.33	0.51	0	5.00	0.37	0.50	0	5
number of full bathrooms	2.43	0.73	1	8	2.58	0.74	1	7
number of bedrooms	3.68	0.79	0	10	3.81	0.80	1	10
the home has energy efficient features	0.27	0.44	0	1	0.27	0.44	0	1
number of garage spaces	2.26	0.67	0	9	2.41	0.69	0	9
up to or less than 3 garage spaces	2.23	0.58	0	3	2.35	0.56	0	3
any additional garage spaces > 3	0.04	0.25	0	6	0.06	0.31	0	6
condition of the home at the time of sale	3.09	0.55	2	5	2.96	0.50	2	5
relatively new or recently renovated (2)	0.10	n/a	0	1	0.14	n/a	0	1
well maintained (3)	0.70	n/a	0	1	0.75	n/a	0	1
minimal repairs (4)	0.19	n/a	0	1	0.11	n/a	0	1
significant repairs (5)	0.004	n/a	0	1	0.001	n/a	0	1
quality of construction	3.57	0.56	2	5	3.49	0.58	2	5
custom designed (1)	0.03	n/a	0	1	0.04	n/a	0	1
high-quality above standard (2)	0.37	n/a	0	1	0.43	n/a	0	1
meet or exceeds codes (3)	0.59	n/a	0	1	0.53	n/a	0	1
basic economy (4)	0.006	n/a	0	1	0.002	n/a	0	1
view from the home	1.23	0.42	1	3	1.23	0.42	1	3
beneficial (2)	0.23	n/a	0	1	0.23	n/a	0	1
neutral (1)	0.77	n/a	0	1	0.77	n/a	0	1
adverse (3)	0.001	n/a	0	1	0.001	n/a	0	1
neighborhood description	1.26	0.62	1	3	1.24	0.59	1	3
beneficial (2)	0.07	n/a	0	1	0.07	n/a	0	1
neutral (1)	0.83	n/a	0	1	0.85	n/a	0	1
adverse (3)	0.10	n/a	0	1	0.08	n/a	0	1
N	**356,013**				**43,673**			
gross solar system replacement cost at the time of sale (nominal $/watt)					$ 4.18	$ 0.46	$ 2.72	$ 7.30
net solar system replacement cost at the time of sale (nominal $/watt)					$ 2.82	$ 0.38	$ 1.37	$ 4.59
present value of energy savings at the time of sale (nominal $/watt)					$ 3.29	$ 0.91	$ -	$ 6.19
gross solar system replacement cost at the time of sale (2020 $/watt)					$ 4.36	$ 0.60	$ 2.65	$ 8.33
net solar system replacement cost at the time of sale (2020 $/watt)					$ 2.87	$ 0.44	$ 1.28	$ 5.11
present value of energy savings at the time of sale (2020 $/watt)					$ 3.42	$ 0.91	$ -	$ 6.18

Source: Author calculations from Fannie Mae CU and TTS merged data.

Table A2: Combined CT, MA and OR Sample Summary Statistics

	Non-Solar Home Transactions				Solar Home Transactions			
description	**mean**	**sd**	**min**	**max**	**mean**	**sd**	**min**	**max**
contract price (1,000s of nominal dollars)	$ 451	$ 241	$ 155	$ 3,050	$ 547	$ 276	$ 160	$ 2,900
natural log of nominal contract price	12.91	0.44	11.95	14.93	13.12	0.42	11.98	14.88
home has non-homeowner owned (NHO) PV system	n/a				0.00	0.00	0	0
size of the PV system (kilowatts)	n/a				5.99	2.65	1	15
age of the PV system at the time of sale (years)	n/a				3.89	2.21	0	15
installed cost of the system (nominal $/watt)	n/a				5.15	1.42	2	10
living area (square feet)	2,022	774	937	5,314	2,156	809	954	5,308
natural log of living area	7.54	0.36	6.84	8.58	7.61	0.36	6.86	8.58
size of parcel (in acres)	0.75	1.06	0.06	9.98	0.82	1.28	0.06	9.85
percent of first acre	0.50	0.34	0.06	1.00	0.50	0.35	0.06	1.00
number of acres greater than 1	0.26	0.87	0	8.98	0.32	1.09	0	8.85
age of the home at time of sale (years)	42.39	27.29	0	114.00	40	28	1	114
number of half bathrooms	0.53	0.56	0	5.00	0.48	0.53	0	2
number of full bathrooms	1.84	0.68	1	7	1.90	0.69	1	7
number of bedrooms	3.40	0.71	0	9	3.43	0.75	1	9
the home has energy efficient features	0.10	0.30	0	1	0.10	0.30	0	1
number of garage spaces	1.94	0.99	0	9	2.09	0.97	0	8
up to or less than 3 garage spaces	1.83	0.72	0	3	1.97	0.66	0	3
any additional garage spaces > 3	0.10	0.47	0	6	0.12	0.51	0	5
condition of the home at the time of sale	3.09	0.58	2	5	3.00	0.51	2	4
relatively new or recently renovated (2)	0.12	n/a	0	1	0.13	n/a	0	1
well maintained (3)	0.67	n/a	0	1	0.74	n/a	0	1
minimal repairs (4)	0.21	n/a	0	1	0.13	n/a	0	1
significant repairs (5)	0.004	n/a	0	1	-	n/a	0	1
quality of construction	3.49	0.59	2	5	3.42	0.60	2	5
custom designed (1)	0.04	n/a	0	1	0.05	n/a	0	1
high-quality above standard (2)	0.43	n/a	0	1	0.48	n/a	0	1
meet or exceeds codes (3)	0.52	n/a	0	1	0.47	n/a	0	1
basic economy (4)	0.008	n/a	0	1	0.002	n/a	0	1
view from the home	1.08	0.28	1	3	1.09	0.29	1	3
beneficial (2)	0.07	n/a	0	1	0.08	n/a	0	1
neutral (1)	0.92	n/a	0	1	0.92	n/a	0	1
adverse (3)	0.003	n/a	0	1	0.004	n/a	0	1
neighborhood description	1.19	0.50	1	3	1.17	0.47	1	3
beneficial (2)	0.09	n/a	0	1	0.09	n/a	0	1
neutral (1)	0.86	n/a	0	1	0.87	n/a	0	1
adverse (3)	0.05	n/a	0	1	0.04	n/a	0	1
N	**86,503**				**2,167**			
gross solar system replacement cost at the time of sale (nominal $/watt)					$ 4.22	$ 0.40	$ 2.95	$ 6.30
net solar system replacement cost at the time of sale (nominal $/watt)					$ 2.57	$ 0.56	$ 0.20	$ 3.75
present value of energy savings at the time of sale (nominal $/watt)					$ 2.25	$ 0.92	$ (0.04)	$ 4.18
gross solar system replacement cost at the time of sale (2020 $/watt)					$ 4.41	$ 0.52	$ 2.96	$ 7.23
net solar system replacement cost at the time of sale (2020 $/watt)					$ 2.60	$ 0.61	$ 0.03	$ 4.08
present value of energy savings at the time of sale (2020 $/watt)					$ 2.34	$ 0.95	$ (0.04)	$ 4.21

Source: Author calculations from Fannie Mae CU and TTS merged data.

10. Appendix B: Cost Estimate Preparation

To calculate both the net and gross cost estimates for each of the PV home transactions at the time of sale, we estimate a two-stage regression as used previously (Hoen et al., 2011; 2013a; 2013b; 2017). This procedure starts with the extensive dataset of more than one million PV homes collected for TTS and their respective gross installed costs as reported (Barbose & Dargouth, 2020), for which the respective net installed costs (i.e., net of federal and state incentives) are calculated using the procedure outlined in Appendix C of Barbose et al. (2019). The first stage uses the net costs as the dependent variable and county, year, system size, and home type (new or existing) as the independent variables, in the following model:

$$C_{itsc} = \alpha + \beta_1(T_i) + \beta_2(S_i) + \beta_3(N_i) + \beta_4(C_i) + \varepsilon_{itsc} \qquad (3)$$

where

C_{itsc} is the "net installed cost" of PV system *i* after state and federal incentives from the full TTS dataset,

T_i is a vector of variables representing the year *t* in which the system was installed,

S_i is a vector of variables representing the size *s* of the system in rounded kilowatts (e.g., 1 kW, 2 kW, 3 kW…),

N_i is a fixed-effect variable indicating if the home was newly built when the system was installed,

C_i is a vector of variables representing the county *c* in which the system was installed,

α is the constant,

$\beta_{1\text{-}4}$ are coefficients for the parameters, and

ε_{itsc} is the error term.

The model accounts for the different state incentives and system component prices over the study period (via T_i), economies of scale (via S_i), different installed costs between new and existing homes (N_i), and the variety of rate structures, installer competitive prices, and market development (via C_i).

Using the predicted coefficients from this model, the data for the set of PV home transactions (county in which the home is located, PV system size, if the home is newly built, and substituting the sale year for the installation year *t*) are fed into the model to produce predicted net cost estimates. These represent, as of the time of sale, the approximate cost to replace a similarly sized system new on the same home.

An identical procedure is followed for gross cost estimates, except, for the first stage, C_{itsc} is the "gross installed cost" of PV system *i* before state and federal incentives from the full TTS dataset.