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Income and racial disparities in financial returns from solar PV deployment☆

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ABSTRACT

Transitioning the U.S. energy system towards renewable sources of energy generation is critical to reducing global CO2 emissions. Solar photovoltaic (PV) technology is a promising source of renewable energy. Federal and state mandates, incentives, and subsidies increase solar PV adoption and hasten the energy transition. However, these policies are designed with adoption as the main metric of success and fail to consider differences in the stream of financial returns that accrue to households depending on the mode of adoption. Our research investigates financial returns to solar PV adoption by system ownership status (leased or owned). We examine the relationship of total and average financial returns to income and race using data on solar PV systems installed as part of the Massachusetts Solar Renewable Energy Certificate (SREC) program from 2014–2018. We find that financial returns that accrue to households for owned systems are over 300% higher on average than for leased systems. We also find that neighborhoods with more low-income and non-White households receive lower financial returns compared to neighborhoods with higher income and more White households, mostly because these households tend to lease their solar panels. Our results illustrate that the form of participation in the solar PV market (leasing or owning) has significant implications for the distribution of financial returns. Policymakers interested in prioritizing equity in the energy transition should account for this difference in financial returns when designing solar adoption programs, especially those targeted towards low-income and non-White communities.

1. Introduction

A transition away from fossil fuels to clean, renewable energy sources is underway globally due to concerns about climate change, health and environmental impacts of fossil-based energy, and geopolitics. Projections of the share of renewables in global electricity generation by 2050 range from 49%–85%, and the United Nations Intergovernmental Panel on Climate Change estimates that renewable energy has to make up more than 80% of global electricity supply to avoid the worst consequences of climate change (Masson-Delmotte et al., 2018). An important aspect of many national and regional policies underpinning the clean energy transition is the concern for equitable distribution of impacts arising from this transition. There is growing recognition of the inequities associated with the current energy system, and politicians and environmental activists alike are placing justice and equity front and center in their platforms. In the United States (US), President Biden's "Build Back Better" plan lists the energy transition as one of four "great national challenges" and specifically mentions addressing environmental injustice (Biden Campaign, 2020). The Green New Deal, a prominent policy roadmap for combatting climate change, lists justice and equity for past, present, and future generations as a key goal (United States House and Congress, 2019). Equity in the energy transition is a focus at the state level as well. Prior to the U.S. rejoining the Paris Climate Agreement, which prioritizes energy equity, twenty-five states independently signed on, signaling broad popular support for equity and justice in the fight against climate change (United States Climate Alliance, 2019). In this context, it is important to evaluate current energy policies and their outcomes in terms of their distributional impacts.

Solar power is being deployed rapidly around the globe, and is expected to be one of the key sources of renewable energy in the coming decades (REN21, 2020). Although the growing adoption of rooftop solar is desirable from an environmental perspective, several recent studies have called attention to disparities in solar PV market participation. Controlling for income and home ownership, Sunter et al.

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(2019) found that majority Black and majority Hispanic neighborhoods in the US installed 69% and 30% less solar PV respectively, compared to no-majority census tracts. In contrast, majority White neighborhoods installed 21% more solar PV systems compared to no-majority census tracts. Similarly, in a study of several cities across the US, Reames (2020) found that although higher solar potential existed in some low and middle income communities, this higher potential did not lead to higher rooftop penetration.

In this paper, we examine the distribution of financial returns from solar PV installations by income and race. This analysis goes beyond using installations as the sole metric of solar PV market participation by examining financial returns which depend on time of installation and importantly, whether panels are leased or owned. Financial returns provide a more nuanced metric of the benefits derived by households from solar market participation. We use data on over 70,000 residential installations in Massachusetts, which account for all residential installations between 2014–2018. We have information on the address location of each solar PV system as well as system characteristics including whether the panels are owned or leased. Using public data on available incentives at time of installation and a cash flow model, we calculate the net present value that accrues to each solar PV system over a 25-year period. We aggregate the individual system returns to obtain total and average financial returns at the census block group level. We investigate disparities in financial returns by race and income by using statistical regressions of financial returns on income and race, along with appropriate controls.

We find that average returns to households from owned systems are $2292 per kW capacity ($16,047 for a typical 7-kWC system) while the average returns from leased systems are $742 per kW capacity ($5199 for a 7-kWC system). These figures imply that financial returns that accrue to households for owned PV systems are on average 300% higher than returns for leased systems. Returns are highly heterogeneous among census block groups with at least one PV installation. For example, in 2016 one block group received about $567 in total financial returns, while another block group received over $595,000. Median household income and percentage of White households in a census block group are significant correlates of financial returns. We find that compared to census block groups with low median income, middle-income and high-income census block groups see higher total returns of over $4251 and $6158, respectively. In addition, middle-income and high-income census block groups see an average return on each installation of over $678 and $2316 respectively. An increase in the percentage of White residents in a census block group is also associated with higher average returns per installation of over $1800. The greater financial returns experienced by higher income and White households can primarily be attributed to higher rates of ownership (rather than leasing) in these groups.

This paper contributes to the literature examining disparities in solar PV adoption (O'Shaughnessy, 2020; Sunter et al., 2019). The results emphasize the need to go beyond using installation of a solar PV system alone as a metric for solar PV market participation to examining financial value that accrues to households from these installations. Leasing has been suggested as an avenue for low-income households to participate in the solar PV market. While leasing can be the only option available for some households, it is also important to recognize that leasing provides less financial value to households compared to owning. The large gap in financial benefits from owning compared to leasing should be considered when designing policies to encourage market participation among low-income and minority communities. Our paper is the first, to our knowledge, to examine the differences in financial returns from solar PV adoption by income and race. Additionally, we calculate these returns using data from verified solar PV installations in the state of Massachusetts, rather than extrapolating solar coverage from models like Google's Project Sunroof (see Sunter et al., 2019; Reames, 2020).

This paper also adds to the literature on the distributional effects of energy policy by highlighting that solar policy incentives have led to disproportionate gains by higher income and racially White households. This supports existing literature showing that racial and ethnic minorities and those of lower socioeconomic status tend to benefit the least from energy policy. For example, carbon policy can be regressive and might place a disproportionate burden on the poor (Fullerton, 2011), and the benefits of government-driven clean energy programs like tax credits and infrastructure investments go predominately to higher-income Americans (Borenstein and Davis, 2016; Zhou and Noonan, 2019). More broadly, this research also contributes to the literature on inequities in the energy sector. Past studies show that low-income and minority households face disproportionate levels of energy insecurity, or the inability to afford to meet energy consumption needs (Brown, 2020; Hernández, 2015; Memmott, 2021). Areas with more racial and ethnic minorities tend to have homes that are less energy efficient, while also having less access to energy efficient technologies like LED lightbulbs (Reames, 2016). Furthermore, the racial gap in energy expenditures remains stark even after controlling for income, location, and other home characteristics (Lyubich, 2020). In this paper, we show that low-income and non-White households are less likely to be recipients of financial gains from rooftop solar deployment.

2. Data

Three major datasets are used in this study. The first is data on household-level solar installations. The second contains demographic characteristics of the census block groups where the solar installations are located. Finally, we obtain data on financial returns to installed solar PV systems from a financial cash flow model.

2.1. Solar PV installations

We obtain data on solar PV installations in Massachusetts (MA) for 2014–2018 from the MA Department of Energy Resources (DOER). The dataset contains over 75,950 unique solar installations and includes information on system type (e.g., residential, commercial), system ownership status (e.g., leased, owned), detailed system information (e.g., nameplate capacity, installation date), and financial information (e.g., renewable energy certificate factor, total installed costs). Solar installations cluster in the most populous areas of the state but are present in nearly every geographic region (see Fig. 1). The solar PV systems in our dataset were part of the MA Solar Renewable Energy Certificate (SREC) II program which was in effect from 2014 to 2018. Virtually all solar installed during this period was included in the SREC program, meaning that our data represents the universe of solar PV installations in the state for the years in our study. In a separate public records request, we obtain the street addresses for all solar PV installations in Massachusetts. We match the system and address data on generation unit name, creating a dataset that allows us to examine demographic characteristics of the census block groups where the solar PV systems are located.

2.2. Demographic information

We collect demographic data on income measures and racial composition from the American Community Survey (ACS), a household survey administered by the U.S. Census Bureau. We use the block group level 5-year estimates for the years 2014 to 2018. Block group demographics are the most granular data publicly available from the ACS. Census block groups are statistical divisions of census tracts, typically containing 600–3000 people.

The ACS provides information on the count of households per block group in a specific income bracket (16 total brackets beginning with "Less than $10,000 per year" and ending with "More than $200,000 per year"). We simplify the data to include three income brackets:

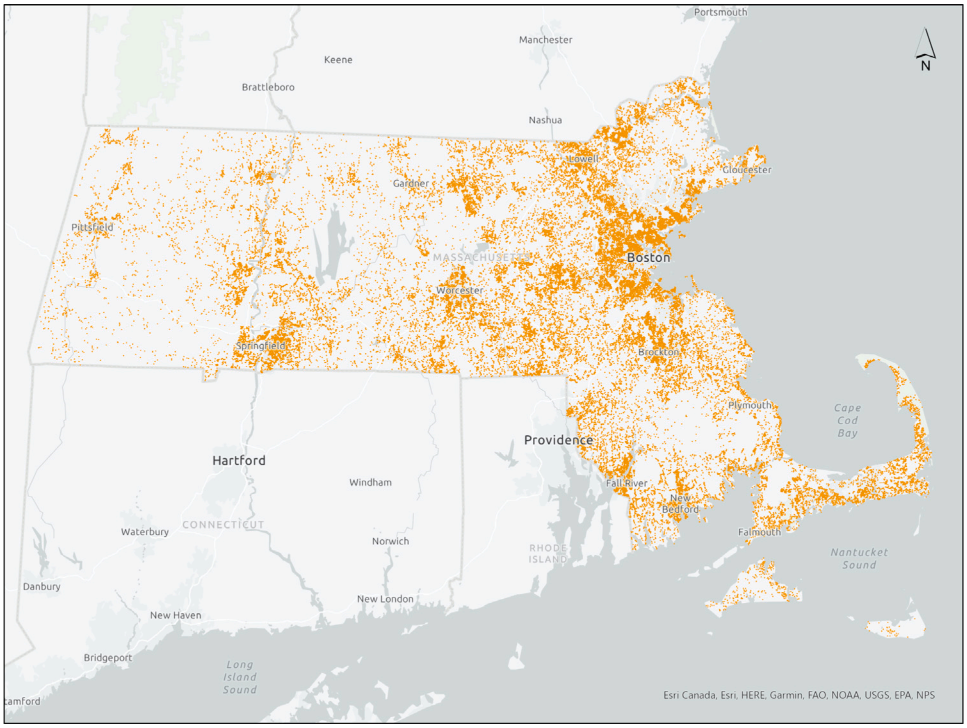


Fig. 1. Location of solar installations in Massachusetts, 2014–2018.

low-income (less than or equal to two-thirds of the median income of $78,772), middle-income (greater than two-thirds of the median income but less than twice the median income), and high-income (equal to or greater than twice the median income).[1]

Our racial composition data include the count of individuals per block group in each racial category, which are White, Black, American Indian and Alaskan Native (AIAN), Asian, Native Hawaiian and Pacific Islander (NHPI), and multiracial (two or more races). We also collect block group level data on the number of owner-occupied households, population density (number of people per square mile), and other demographic characteristics.

2.3. Financial cash flow model

We use a financial cash flow model specifically designed for the state of Massachusetts to estimate financial returns from solar PV installations. The model incorporates realistic assumptions about the costs and benefits of solar PV ownership or leasing, including electricity output of panels, electricity rates, net metering discounts, tax credits, SREC prices, loan interest rates, and operations and maintenance costs.[2,3]

[1] Our income categorizations are based on the method used by the Pew Research Center (2021). This income categorization is also consistent with how the state of Massachusetts defines Environmental Justice Populations, where low income is defined as those with less than or equal to two-thirds the state median income (Mass.gov, 2022).

[2] Solar panel adopters may have the choice to install different panel technologies such as monocrystalline or polycrystalline panels. While our financial model does not explicitly differentiate between the cost or efficiency of panels by technology, the yearly cost and energy output of installation implicitly reflects the average cost and capacity factor of panel installation from the two types of technology depending on their share in the market.

[3] The financial model considers the impacts of state and federal tax incentives and Solar Renewable Energy Credits on the solar investment. The secondary issue of who pays for these incentives and the distribution of these costs across wealth and racial dimensions is an important equity issue in solar policy as this technology comes to scale. However, this evaluation is beyond the scope of this research analysis and paper.

Table 1
Key assumptions of financial cash flow model.

Time horizon	25 years	
Discount rate for NPV	5%	
Operation & maintenance	$21 per kW per year	
	10-yr inverter replacement at $750 per kW	
Electricity rate ($ per kWh)	$0.18	
Electricity rate escalation per year	5%	
	Own	Lease
Electricity rate discount	NA	15%
Project cost financed*	100%	40%
Financing interest rate*	5%	6%
Loan term*	10 yrs	5 yrs

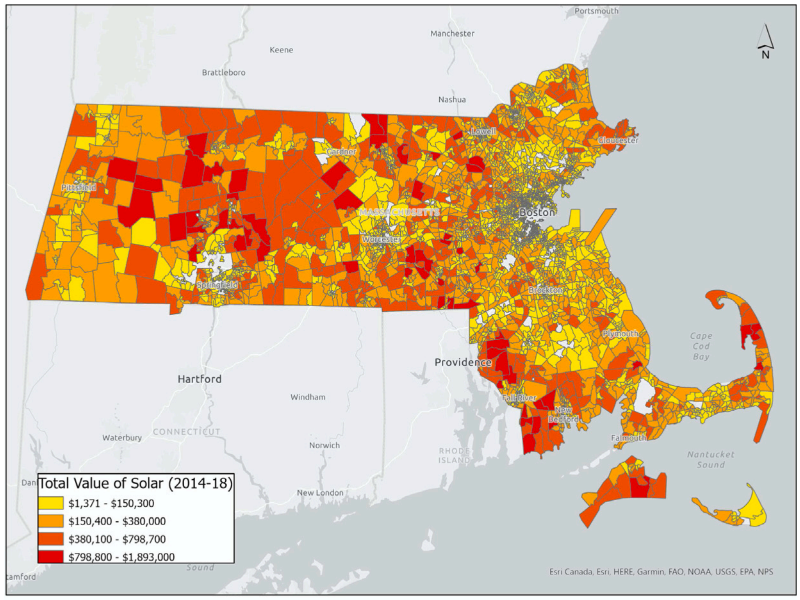
*For own option, this pertains to household. For lease option, this pertains to third-party owner.

Table 2
Income and racial composition of solar block groups compared to state.

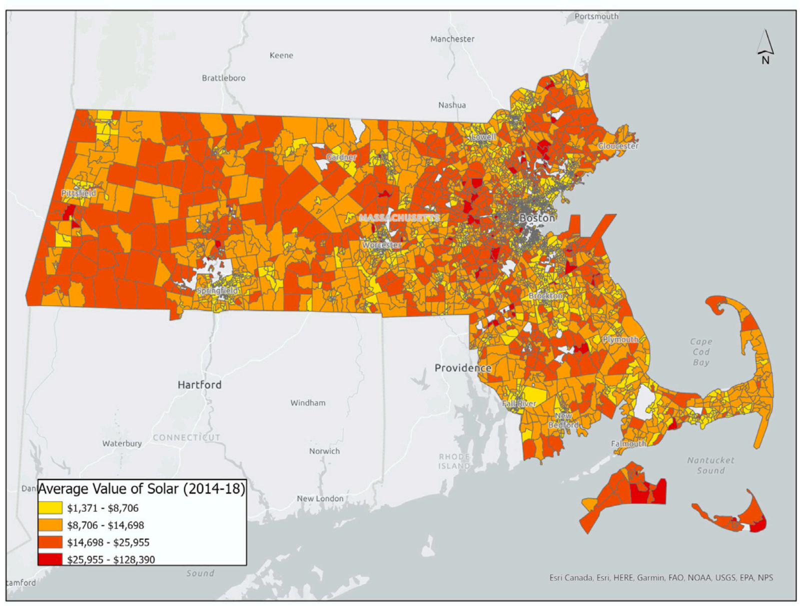
	Massachusetts	Solar block groups
Total number of households	2,845,816	73,458
Median household income	$78,772	$84,416
Race		
White	79.2%	82.2%
Black or African American	7.2%	6.3%
American Indian and Alaska Native	0.2%	0.2%
Asian	6.1%	5.3%
Native Hawaiian or Pacific Islander	0.0%	0.0%
Two or more races	2.5%	2.6%
Other race	4.1%	–

Key assumptions are given in Table 1 The financial model estimates a unique 25-year net present value (NPV) for each installation type (e.g., residential, commercial, community-shared, etc.) and ownership status (e.g., leased, owned) for each year. In this research, we use the information on residential installations, both direct owned and third party owned.

The financial model also calculates the financial returns that accrue to different participants in the solar market. For residential



(a) Total returns



(b) Average returns

Fig. 2. Spatial distribution of total and average financial returns, 2014–2018.

Table 3
NPV of financial returns from solar PV for an average 7-kW capacity system.

		2014	2015	2016	2017	2018	Average
Owning	Household	$13,749	$14,200	$16,347	$17,309	$18,632	$16,047
	Total	$13,749	$14,200	$16,347	$17,309	$18,632	$16,047
Leasing	Third-Party owner	$7571	$7778	$9305	$9928	$10,797	$9076
	Household	$4705	$4940	$5187	$5446	$5719	$5199
	Total	$12,275	$12,718	$14,492	$15,375	$16,516	$14,275

installations, the model calculates returns to the household hosting the solar PV system as well as the third-party owner (TPO) of the solar PV system if the system is being leased. In the case of direct ownership, the cost to households includes an upfront cost to pay for the solar PV system as well as maintenance costs throughout the 25-year lifetime of the solar panels. The financial benefits to the household include electricity bill savings and available incentives including tax credits, rebates, and SRECs.[4] In the case of leasing, the TPO pays for installation and maintenance costs. The TPO also receives all available incentives.

[4] Under the MA SREC program, solar PV owners receive one SREC for every 1000 kWh (1 MWh) produced by their panels. These SRECs can be sold in the open market, where utilities purchase them to meet their obligations under the MA Renewable Portfolio Standard and solar "carve-out" program. Between 2014 and 2018, SREC prices ranged from $275-$385. Given these prices, the owners of an average 7-kW capacity solar PV system could expect

Households hosting the solar panels either pay a leasing fee for the panels or purchase electricity produced by the solar panels under a power purchase agreement. We assume that the financial returns to households and third-party owners are the same under a standard leasing contract and a power purchase agreement. This is reasonable since leasing fees and electricity discounts can be set to yield the same profit for the third-party owner.

We assign a financial return to each of the solar PV installations in our dataset based on year of installation and mode of participation (ownership or leasing). These installation-level financial returns are then aggregated to obtain total and average financial returns at the block group level. Detailed information on assumptions used in the financial model are provided in the University of Massachusetts Clean Energy Extension website (Clean Energy Extension, 2021).

3. Empirical analysis and results

3.1. Demographic characteristics of solar and non-solar households

Our sample of solar households is geographically representative of Massachusetts but differs significantly from state averages for race and household income. The 73,458 households with solar installations represent about 3% of all Massachusetts households. Nearly every census block group is represented, with at least one solar installation appearing in 99% of block groups during the lifetime of the SREC II program. However, solar PV installations are more densely concentrated in block groups that are significantly more racially White and that have higher median income than the state as a whole. Table 2 shows the 5-year average demographic characteristics of households in the state compared to that of census block groups that have solar PV systems during the years in our study. The average median income for block groups with solar households over the five-year study period is \$84,416 while the average state median income is \$78,772. Block groups with solar households also have more racially White residents at 82.2%, compared to the state average of 79.2%. These demographic differences in income and racial composition between block groups with and without solar provide initial evidence for inequities in solar market participation.

3.2. Financial returns for owned systems and leased systems

Table 3 shows the NPV of financial returns to households and third-party owners, depending on whether the solar PV system is bought outright or leased from a third-party owner. Households that own their solar PV systems gain the full financial returns from their investment, while for leased systems the third-party owner captures majority of the financial returns. Table 3 also shows that the NPV of owning and leasing solar PV systems have increased over time. The NPV of owning is around three times that of leasing, and the NPV of owning compared to leasing has increased over time. In 2018, calculations from the financial model show that average returns to households for owned systems are \$2662 per kW capacity (\$18,632 for a typical 7-kWC system) while the average return for leased systems is \$817 per kW capacity (\$5719 for a 7-kWC system).

The NPV of financial returns to individual households that installed solar PV systems were aggregated at the census block group level. Fig. 2 shows the spatial distribution of total and average financial returns in the state. Some clustering of areas with high total or average financial returns are evident, although the clusters are different for total financial returns compared to average financial returns.

Table 4 shows trends in solar PV installations over time, including statistics on financial returns by census block group. Table 4 shows that financial returns are highly heterogeneous among block groups. For example, in 2016, one block group received \$567 in total financial returns, whereas another block group received nearly \$600,000.

to receive between \$2117 and \$2964 from selling their SRECs assuming each kW capacity produced 1.1 MWh of electricity.

Table 4 also shows that the total number of new solar installations varies year by year, peaking in 2016 at about 24,000 new installations and leveling off to about 11,000 per year for the final two years. Leasing is the more popular mode of market participation, with 64% of systems leased between 2014–2018. However, in 2017, the share of owned systems almost equaled that of leased systems, and in 2018 there were more owned systems than leased systems. The share of lessees relative to owners decreased in 2017 and 2018 compared to earlier years due to the introduction of the Massachusetts Solar Loan Program which worked with lenders to stimulate and incentivize solar lending to potential owners of solar PV systems. The total number of installations also dropped in 2017 and 2018 relative to 2015 and 2016 likely due to the end of the SREC II program and net-metering caps being met in utility regions across the state.

3.3. Regression analysis

3.3.1. Financial returns and income

In this section we investigate the relationship between financial returns to solar PV adoption and income. Fig. 3 shows the relationship of financial returns and installations to median income. The relationship of total returns and median income is generally positive and plateaus for very high-income levels (Panel (a)). Average returns per installation shows a positive and near-linear relationship to median income (Panel (b)). Total number of installations and median income exhibits a positive relationship for low to middle income levels and a negative relationship for income levels roughly exceeding the median income in the state (Panel (c)). While the relationships depicted in Fig. 3 are suggestive, they do not control for the effect of other mediating factors, nor do they provide information on the statistical significance of the relationships.

To examine the relationship of income and race to financial returns we use a regression approach. Regression analysis allows us to estimate the relationship between financial returns and income (or race), controlling for other factors that may confound the estimates. Recall that total financial returns is affected by the relative shares of owners and lessees, as well as the number of installations, while average financial returns are a function of the relative shares of owners and lessees. In our preferred specifications, we control for the number of owner-occupied houses and population density. We also include county and year fixed effects (FE). A greater number of owner-occupied houses increases the available pool of households that can adopt solar PV systems since they own their house and can make changes to its structure. In addition, households in owner-occupied houses may have greater incentives to own since they will benefit directly from electricity savings afforded by a solar PV system. Population density can also affect solar PV adoption as very dense areas may have taller, apartment-type buildings with less total rooftop space for solar PV systems. Year to year variation in other variables common to all block groups in the state that affect solar PV adoption (and thus the number of installations) such as electricity prices, available incentives, and familiarity with solar PV technology are accounted for by year fixed effects. Finally, time invariant county-specific characteristics that may affect solar adoption are captured by county fixed effects.[5] Formally, the ordinary least squares (OLS) regression equation is:

$$y_{it} = \beta_0 + \beta_1 x_{it} + \beta_2 z_{it} + T_t + C_j + e_{it} \quad (1)$$

where y_{it} is the dependent variable (total financial returns or average (per installation) financial returns) in census block group i in year t. x_{it} is median income (or race share), z_{it} are control variables, T_t

[5] Other variables identified in the literature as being associated with solar adoption such as average age, educational attainment and Democratic Party affiliation were also included in preliminary regressions, but were found to be not significant and did not improve overall model fit.

Table 4
Trends in solar PV installations and financial returns.

Year	Category	Num. Installs	Num. MW	Mean Return	Min Return	Max Return
2018	Total	10,852	84.32	$50,760	$1,687	$645,520
	Leased	4776	34.27	$8816	$0	$120,358
	Owned	6076	50.05	$41,944	$0	$603,761
2017	Total	11,722	83.37	$50,760	$1237	$609,871
	Leased	6111	40.88	$9775	$0	$131,783
	Owned	5611	42.49	$32,284	$0	$609,871
2016	Total	23,859	174.62	$56,119	$567	$595,151
	Leased	17,376	124.84	$24,866	$0	$298,165
	Owned	6483	49.78	$31,252	$0	$470,244
2015	Total	18,436	129.38	$41,623	$1080	$662,908
	Leased	13,343	93.69	$19,867	$0	$271,362
	Owned	5093	35.69	$21,756	$0	$543,335
2014	Total	5402	34.52	$18,512	$1176	$293,366
	Leased	3118	20.22	$6037	$0	$69,362
	Owned	2284	14.3	$12,474	$0	$293,366

Table 5
Relationship of financial returns and median income.

Panel A: Dependent variable : Total returns	OLS	OLS	OLS	RE
Median income ($)	0.189***	0.081***	0.081***	0.074***
	(0.012)	(0.012)	(0.014)	(0.013)
Owner Occ HH		65.958***	65.958***	49.295***
		(2.073)	(3.566)	(2.953)
Popn density		−1.096***	−1.096***	−1.131***
		(0.061)	(0.069)	(0.067)
Constant	28 393.878***	−4121.756*	−4121.756	650.742
	(1069.662)	(2232.868)	(3210.238)	(3022.361)
Year and county FE	No	Yes	Yes	Yes
Clustered Std. Err.	No	No	Yes	Yes
Observations	15 367	15 367	15 367	15 367
Adjusted R^2	0.017	0.232	0.232	–
Panel B: Dependent variable : Average returns				
Median income ($)	0.055***	0.046***	0.046***	0.032***
	(0.002)	(0.002)	(0.002)	(0.002)
Owner Occ HH		1.698***	1.698***	1.703***
		(0.294)	(0.350)	(0.354)
Popn density		−0.072***	−0.072***	−0.082***
		(0.009)	(0.010)	(0.010)
Constant	5939.213***	4090.734***	4090.734***	5185.238***
	(147.156)	(316.467)	(307.943)	(323.229)
Year and county FE	No	Yes	Yes	Yes
Clustered Std. Err.	No	Yes	Yes	Yes
Observations	15 367	15 367	15 367	15 367
Adjusted R^2	0.074	0.231	0.231	–

Note: OLS — ordinary least squares, RE — random effects.
Standard errors in parentheses.
*p < 0.10.
***p < 0.01.

are year fixed effects, C_j are county fixed effects, and e_{it} is the error term. We also employ a random effects (RE) panel estimator to account for possible unobserved heterogeneity. The RE regression equation is similar to (1) except that the error term is re-written as $\mu_{it} = v_i + e_{it}$ where v_i is the random census block group-specific effect. Summary statistics of variables included in the regression analyses in this section are presented in Table A.1.

It is possible that installations of solar PV are influenced by a census block group's proximity to other CBGs. Papers such as Graziano and Gillingham (2015) have shown clustering in solar PV installations. To address concerns of possible spatial autocorrelation, we implement standard error correction using the approach developed by Colella et al. (2020) as a robustness check. Results are presented in Table A.2.

Table 5 panel A shows regressions of total financial returns on median income and controls while panel B shows regressions of average financial returns on median income and controls. For total financial returns, the results in panel A show that after controlling for owner occupancy and population density, and including fixed effects, the positive relationship of financial returns to median income is highly statistically significant. In the RE specification, results show that a $10,000 increase in median income is associated with higher returns of $740 in a census block group. For average financial returns, the results in panel B show that the relationship of average financial returns and median income is also positive and statistically significant. A $10,000 increase in median income is associated with greater average financial returns of $320 per solar PV installation.

Two factors contribute to greater total financial returns in a block group: greater number of installations and more owned systems. For average financial returns, its value can only increase when there are more owned systems relative to leased systems. To examine the role of installations and owned systems we regress number of installations and number of owned systems on median income and other controls as in Eq. (1). Because the number of installations and owned systems are count variables, we also include a negative binomial (NB) specification

Table 6
Relationship of number of installations and number of owned systems to median income.

	No. of installations			No. of owned systems		
	OLS	RE	NB	OLS	RE	NB
Median income ($)	−0.000007***	−0.000004***	−0.000002***	0.000007***	0.000006***	0.000005***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Owner Occ HH	0.005972***	0.004030***	0.001176***	0.002016***	0.001509***	0.001109***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Popn density	−0.000097***	−0.000098***	−0.000035***	−0.000026***	−0.000028***	−0.000034***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Constant	1.494791***	1.757709***	0.698526***	0.237115	0.441107***	−0.509111***
	(0.277)	(0.265)	(0.052)	(0.183)	(0.171)	(0.097)
Year and county FE	Yes	Yes	Yes	Yes	Yes	Yes
Clustered Std. Err.	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15 367	15 367	15 367	15 367	15 367	15 367
Adjusted R^2	0.243			0.206		

Note: OLS — ordinary least squares, RE — random effects, NB — negative binomial.
Standard errors in parentheses.
***p < 0.01.

Table 7
Relationship of financial returns and income groups.

Panel A: Dependent variable : Total returns	OLS	OLS	OLS	RE
Omitted category: Low income				
Middle income	19 135.729***	5341.086***	5341.086***	4251.078***
	(1119.729)	(1111.972)	(1254.397)	(1076.354)
High income	18 159.524***	7984.803***	7984.803***	6157.922***
	(1863.158)	(1765.581)	(1704.891)	(1553.386)
Owner Occ HH		67.200***	67.200***	49.676***
		(2.043)	(3.626)	(2.961)
Popn density		−1.105***	−1.105***	−1.130***
		(0.059)	(0.067)	(0.066)
Constant	28 600.666***	−3860.917*	−3860.917	1579.887
	(997.854)	(2236.300)	(3207.459)	(3023.789)
Year and county FE	No	Yes	Yes	Yes
Clustered Std. Err.	No	No	Yes	Yes
Observations	15 760	15 758	15 758	15 758
Adjusted R^2	0.018	0.230	0.230	
Panel B: Dependent variable : Average returns				
Omitted category: Low income				
Middle income	2186.505***	1192.717***	1192.717***	678.191***
	(159.855)	(161.687)	(175.667)	(161.181)
High income	5238.163***	4052.539***	4052.539***	2316.420***
	(265.989)	(256.725)	(309.800)	(300.897)
Owner Occ HH		3.390***	3.390***	2.725***
		(0.297)	(0.339)	(0.328)
Popn density		−0.102***	−0.102***	−0.101***
		(0.009)	(0.010)	(0.010)
Constant	8617.380***	5460.914***	5460.914***	6273.390***
	(142.456)	(325.170)	(320.063)	(327.047)
Year and county FE	No	Yes	Yes	Yes
Clustered Std. Err.	No	No	Yes	Yes
Observations	15 760	15 758	15 758	15 758
Adjusted R^2	0.025	0.207	0.207	

Note: OLS — ordinary least squares, RE — random effects.
Standard errors in parentheses.
*p < 0.10.
***p < 0.01.

as a robustness check. Table 6 shows that median income has a negative relationship with the number of installations and a positive relationship with system ownership. A $10,000 increase in median income is associated with 0.04 less installations and 0.06 more owned systems in a block group. These results show that greater number of owned systems is likely driving higher financial returns among higher income households.

We also investigate financial returns by income brackets. We categorize block groups according to whether the median income falls in the low income (less than or equal to two-thirds of state median income of $78,772), middle income (greater than or equal to two-thirds of state median income and less than 2 times the median income), and high income (greater than or equal to 2 times the median income) category. Table 7 panel A shows that compared to block groups with median income in the low income category, middle and high income block groups obtain significantly higher total financial returns of $4251 and $6157 respectively (RE specification). Table 8 shows that for middle income groups, this is because of both greater number of installations and owned systems. For high income groups, the higher returns are only due to a greater number of owned systems. As shown in Table 8, relative to the low income group, the high income group had a fewer number of installations. The results for regressions of average returns in Table 7 panel B show that compared to low-income block groups, middle income and high-income block groups see a higher average

Table 8
Relationship of number of installations and number of owned systems to income groups.

	No. of installations			No. of owned systems		
	OLS	RE	NB	OLS	RE	NB
Omitted category: Low income						
Middle income	0.210*	0.172	0.042	0.317***	0.222***	0.336***
	(0.103)	(0.092)	(0.023)	(0.050)	(0.044)	(0.041)
High income	−0.544***	−0.304*	−0.138***	0.654***	0.446***	0.512***
	(0.136)	(0.126)	(0.034)	(0.072)	(0.068)	(0.050)
Owner Occ HH	0.005***	0.004***	0.001***	0.002***	0.002***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Popn density	−0.000***	−0.000***	−0.000***	−0.000***	−0.000***	−0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Constant	1.036***	1.493***	0.586***	0.357*	0.567***	−0.490***
	(0.280)	(0.269)	(0.054)	(0.185)	(0.173)	(0.106)
Year and county FE	Yes	Yes	Yes	Yes	Yes	Yes
Clustered Std. Err.	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15 758	15 758	15 758	15 758	15 758	15 758
Adjusted R^2	0.242			0.199		

Note: OLS — ordinary least squares, RE — random effects, NB — negative binomial.
Standard errors in parentheses.
*p < 0.10.
***p < 0.01.

Table 9
Relationship of financial returns and racial composition.

Panel A: Dependent variable : Total returns						
% White	533.741					
	(2339.662)					
% Black		1380.825				
		(2551.609)				
% Asian			−3495.749			
			(5198.940)			
% Native Am				10 914.171		
				(58 259.495)		
% Native HPI					167 812.401	
					(128 416.870)	
% Multiracial						6002.863
						(9289.671)
Constant	183.117	523.850	695.930	−5299.614*	−5339.594*	508.211
	(3460.515)	(3053.528)	(3019.001)	(3058.197)	(3031.326)	(3034.362)
Observations	15 367	15 367	15 367	15 367	15 367	15 367
Panel B: Dependent variable : Average returns						
% White	1805.297***					
	(493.968)					
% Black		−1778.877***				
		(538.181)				
% Asian			133.385			
			(892.290)			
% Native Am				−180.920		
				(7634.732)		
% Native HPI					−1245.350	
					(19 087.486)	
% Multiracial						−2779.864
						(1785.641)
Constant	3673.098***	5319.106***	5183.673***	4809.898***	4810.701***	5248.441***
	(536.258)	(324.031)	(322.690)	(322.510)	(321.258)	(322.841)
Observations	15 367	15 367	15 367	15 367	15 367	15 367

Standard errors in parentheses.
Regressions control for median income, number of owner occupied households, and population density.
All regressions include year and county fixed effects using RE specifications.
*p < 0.10.
***p < 0.0.

return on their solar systems. Notably, the increase in average returns for the high-income block groups relative to low-income block groups is substantially larger at $2316 compared to the increase in average return for the middle-income block groups relative to low-income block groups at $678 (RE specification).

Our NPV calculations of financial returns assume that households have the same discount rate. Studies have suggested that lower discount rate is associated with higher income (Epper et al., 2020). Crago and Rong (2022) give empirical evidence that those with lower discount rate are more likely to choose ownership rather than leasing of solar panels. If higher income households indeed have lower discount rates, and are more likely to be owners, accounting for heterogeneity in discount rates among households is likely to exacerbate the inequity in financial returns from solar PV deployment between high income and low income households.

Table 10
Relationship of number of installations and number of owned systems to racial composition.

	Installations	Owned systems	Installations	Owned systems	Installations	Owned systems
% White	−0.154	0.355***				
	(0.201)	(0.086)				
% Black			0.533**	−0.373***		
			(0.264)	(0.094)		
% Asian					−0.898**	0.052
					(0.384)	(0.199)
Observations	15 367	15 367	15 367	15 367	15 367	15 367

Standard errors in parentheses.
Regressions control for median income, number of owner occupied households and population density.
All regressions include year and county fixed effects using RE specifications.
**p < 0.05.
***p < 0.0.

Table 11
Trends in the relationship of financial returns and income over time.

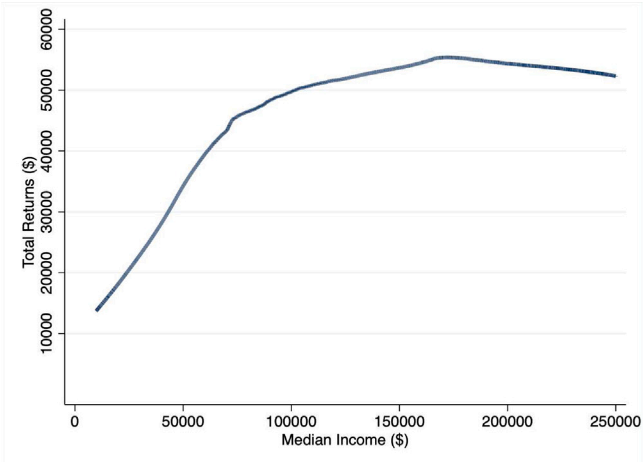
Panel A: Dependent variable : Total returns					
	2014	2015	2016	2017	2018
Median income ($)	0.110***	0.060***	0.031	0.120***	0.139***
	(0.014)	(0.022)	(0.035)	(0.024)	(0.026)
Owner Occ HH	26.734***	117.371***	56.427***	28.107***	107.872***
	(2.379)	(3.807)	(5.804)	(4.065)	(4.488)
Popn density	−0.241***	−0.642***	−1.801***	−0.941***	−0.313**
	(0.089)	(0.135)	(0.143)	(0.106)	(0.142)
Constant	236.630	−10 694.589***	64 070.277***	33 272.941***	11 072.039**
	(2460.803)	(3498.083)	(5476.968)	(3938.443)	(4437.730)
Observations	2257	3254	3607	3141	3108
Adjusted R^2	0.153	0.368	0.158	0.182	0.310
Panel B: Dependent variable : Average returns					
	2014	2015	2016	2017	2018
Median income ($)	0.038***	0.032***	0.041***	0.043***	0.069***
	(0.004)	(0.003)	(0.003)	(0.004)	(0.004)
Owner Occ HH	0.780	0.728	2.015***	1.929***	2.699***
	(0.576)	(0.557)	(0.572)	(0.732)	(0.773)
Popn density	−0.061***	−0.057***	−0.064***	−0.093***	−0.064***
	(0.022)	(0.020)	(0.014)	(0.019)	(0.024)
Constant	4402.588***	4380.490***	5595.841***	9756.053***	10 515.501***
	(596.231)	(512.151)	(539.602)	(709.445)	(764.292)
Observations	2257	3254	3607	3141	3108
Adjusted R^2	0.120	0.083	0.114	0.107	0.156

Standard errors in parentheses.
Regressions control for median income, number of owner occupied households and population density.
All regressions include year and county fixed effects using RE specifications.
**p < 0.05.
***p < 0.01.

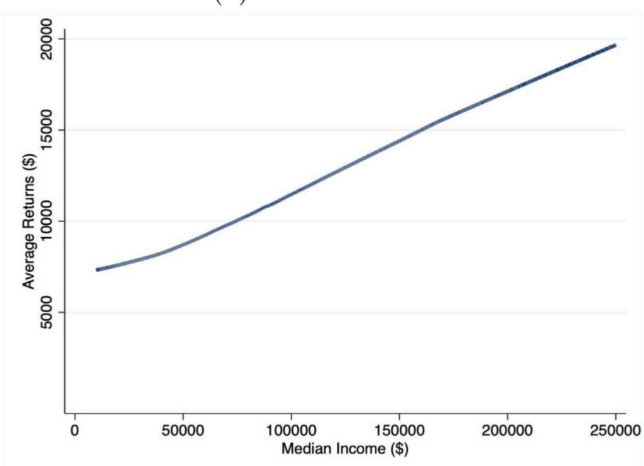
Table 12
Trends in the relationship of financial returns and racial composition over time.

Panel A: Dependent variable : Total returns					
	2014	2015	2016	2017	2018
% White	−6372.301**	4565.648	24 121.005***	18 037.458***	8045.718
	(2995.919)	(4598.061)	(6730.421)	(5159.218)	(5787.078)
% Black	2769.062	−1916.413	−24 502.249***	−16 957.352**	−12 693.487
	(4184.629)	(6089.659)	(9018.393)	(7255.527)	(8040.970)
% Asian	16 967.814***	−21 563.515**	−18 717.750	−15 976.455	−10 168.870
	(6219.207)	(9322.254)	(13 670.704)	(10 213.446)	(11 260.521)
Panel B: Dependent variable : Average returns					
	2014	2015	2016	2017	2018
% White	1905.854***	1762.305***	2905.691***	4903.539***	3306.274***
	(731.125)	(657.427)	(656.899)	(890.410)	(951.230)
% Black	−2798.975***	−2547.712***	−3580.136***	−5359.510***	−2615.755**
	(1020.128)	(870.391)	(879.909)	(1253.243)	(1323.562)
% Asian	16 967.814***	−21 563.515**	−18 717.750	−15 976.455	−10 168.870
	(6219.207)	(9322.254)	(13 670.704)	(10 213.446)	(11 260.521)

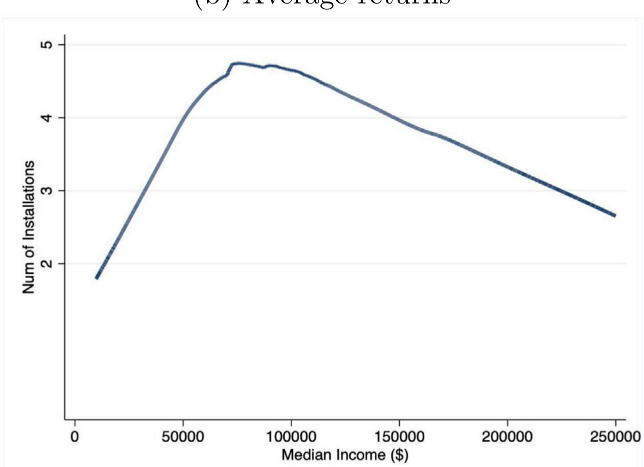
Standard errors in parentheses. This table presents only the coefficient on racial group.
The regressions also control for median income, number of owner occupied households, and population density.
**p < 0.05.
***p < 0.01.



(a) Total returns



(b) Average returns



(c) Number of installations

Fig. 3. Relationship of financial returns and installations to median income,2014–2018. Lines represent results from Locally Weighted Scatterplot Smoothing (LOWESS) regressions between the two variables in each panel.

3.3.2. Financial returns and race

Next, we examine the relationship between financial returns and race. Table 9 shows results of regressions of total and average financial returns on population share of different racial groups, controlling for income, owner occupancy and population density. The results from Table 9 show that the relationship of total financial returns to racial composition is not statistically significant while the relationship of average financial returns to White and Black racial composition is significant. The results from Panel B show that average financial returns increase with percentage White residents and decrease with percentage Black residents: A percentage point increase in the share of White residents is associated with an increase of $1805 in average financial returns while a percentage point increase in the share of Black residents is associated with a decrease of $1778 in average financial returns.

Recall that total financial returns are determined by number of installations and whether a system is owned or leased, while average financial returns depend only on the number of owned systems. The results in Table 9 suggest that there is greater ownership of solar PV systems in areas with more White residents, and less ownership in areas with more Black residents. The results in Table 10 confirm this by showing that the percentage of White residents is not significantly correlated with more installations but is significantly (and positively) correlated with number of owned systems. The percentage of Black residents is significantly correlated with more installations but is significantly (and negatively) correlated with ownership. This means that although the number of installations is increasing with the share of Black residents, these solar PV systems are not owned and thus average returns are lower.

To examine how financial gains are distributed across racial groups, we calculate the share of total financial returns accruing to each racial group compared to its population share. The bars in Fig. 4 are generated by multiplying the financial return at the block group level by the share of people in each racial group. A key assumption here is that distribution of returns is the same as the racial distribution in a block group. If the distribution of solar PV is skewed to White residents, the results presented are conservative, and disparities are greater than what we report. Fig. 4 shows that as expected, White residents obtain disproportionately more financial returns, while other racial groups obtain lower financial returns.

Table A.1
Summary statistics.

	No. of Obs	Mean	Std. Dev.	Min	Max
Median HH income ($)	15,367	84,535	38,567	9,730	250,001
% Low income	15,763	0.19	0.39	0	1
% Middle income	15,763	0.73	0.44	0	1
% High income	15,763	0.08	0.27	0	1
No. Owner-occupied HH	15,758	368	213	–	1643
Population density (Persons per sq. mile)	15,758	5445	7924	–	115,149
% White	15,745	0.82	0.19	0	1
% Black	15,745	0.06	0.13	0	1
% Asian	15,745	0.05	0.08	0	0.89
% Native Am	15,745	0	0.01	0	0.47
% Native HPI	15,745	0	0.01	0	0.55
% Multiracial	15,745	0.03	0.04	0	0.54

3.3.3. Trends over time

In this section, we look at trends over time. Table 11 shows the relationship of financial returns and median income for the individual years in our study, from 2014 to 2018. The results in Table 11 panel A show that total returns and median income have a significant and positive relationship for most years and the strength of this association has increased over time as evidenced by the increasing magnitude of the coefficients of median income in later years. Table 11 panel B shows a similar trend for average financial returns, implying increasing ownership among higher income groups over time.

Table 12 Panel A shows that the relationship of total returns and population share of different racial groups did not show a consistent trend over time. Table 12 Panel B shows that average returns are positively related with percentage While residents across the different

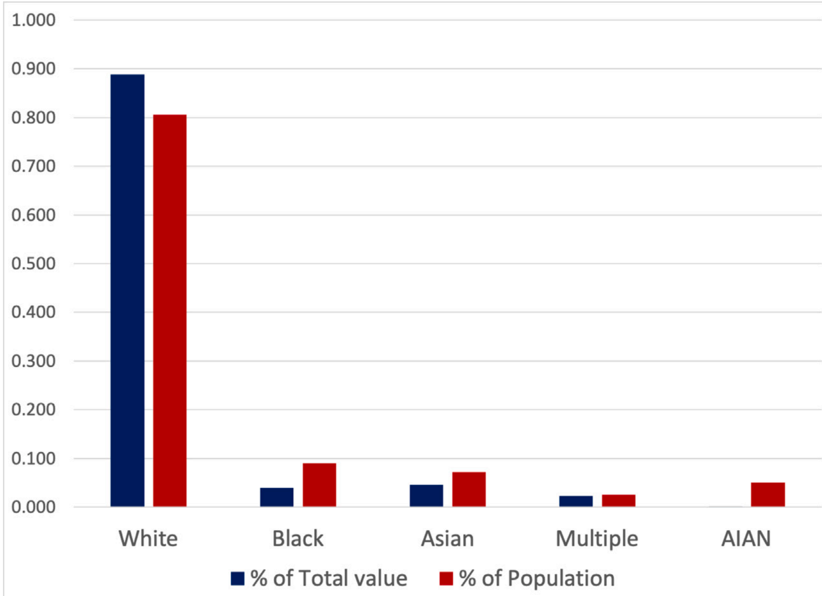


Fig. 4. Share of total financial returns relative to population share of different racial groups.

Table A.2
Robustness checks for spatial autocorrelation.

	Total returns		Average returns	
Standard errors adjusted for spatial autocorrelation:	No	Yes	No	Yes
Median income ($)	0.081***	0.081***	0.046***	0.046***
	(0.014)	(0.020)	(0.002)	(0.003)
Owner Occ HH	65.958***	65.958***	1.698***	1.698***
	(3.566)	(6.412)	(0.350)	(0.376)
Popn density	−1.096***	−1.096***	−0.072***	−0.072***
	(0.069)	(0.224)	(0.010)	(0.023)
Constant	−4121.756	−4121.756	4090.734***	4090.734***
	(3210.238)	(7189.261)	(307.943)	(452.856)
Year and county FE	Yes	Yes	Yes	Yes
Clustered std. err.	Yes	No	Yes	No
Observations	15 367	15 367	15 367	15 367

Columns 1 and 3 replicate results from Table 5. Standard errors in parentheses.
***$p < 0.01$.

years and the coefficient magnitudes are higher in later years suggesting greater ownership in areas with more White residents over time. For Black residents, average returns are negatively associated with percentage Black residents across the different years. However, the coefficient magnitudes do not exhibit a clear trend to suggest that the lower rates of ownership among Black residents is being exacerbated over time.

4. Conclusion

We have shown that financial returns from household participation in the solar PV market are positively related to higher income and the proportion of White residents in a block group. These higher financial returns are driven partly by a greater number of installations, and more importantly, whether the solar PV systems are owned or leased. Owned systems yield greater returns for solar households because these households can access financial incentive payments from the sale of SRECs that can constitute 50%–90% of the net present value of the solar PV investment and from the federal tax credit which is 30% of installation cost. Higher income residents have greater opportunity for system ownership due to their access to investment capital and sufficient tax appetites for the federal credits. That these government incentives are primarily going to wealthier and Whiter households call for further policy measures to assure renewable energy technologies and ownership can be equitably accessible across all types of households.

The availability of an ownership option and a leasing option creates opportunities for optimal sorting of consumers based on their preferences and endowments. While the literature on the determinants of a household's decision to own or lease solar PV systems is thin, a paper by Rai and Sigrin (2013) suggests that households in the state of Texas that lease tend to be cash constrained compared to household that chose to own their panels. This is reasonable because buying solar panels outright does entail capital expenditures either from household savings or from financing (which also requires good financial standing). Another paper by Pless et al. (2020) based on households in California finds that owners and lessees of solar panels differ in the types of information sought prior to the adoption decision. Those that eventually bought their system outright looked for information on financial returns while those that eventually leased their systems looked for information about modifications to their housing structure to accommodate solar panels. The findings from Pless et al. (2020) suggest greater attention to financial return for eventual owners. The importance of ownership in determining financial returns to solar PV adoption and the relative lack of studies examining factors affecting the decision to own or lease call for more research in this area. Future studies that explore this decision can also improve upon using income as a metric for wealth as in Tidemann et al. (2019).

The role of ownership in increasing financial returns also brings up the question of whether ownership should be incentivized by government programs. To some extent, state and local governments already offer additional incentives for low income households to encourage solar market participation and ownership. For example, the state of Massachusetts' SMART program, which provides preferential rates for solar electricity has additional incentives for low income households. As mentioned above, if the option to own or lease acts as an efficient sorting strategy for market participants, there is no policy intervention required in the solar PV market. However, it is also possible that households are electing to lease rather than own due to lack of adequate information about the financial advantages of owning versus leasing or due to lack of access to financing. From a policy perspective, it is important to determine whether households are making choices based on limited information about the options available to them. Further studies into what types of information are available to solar PV adopters will be helpful in determining whether educational programs are needed to help households maximize their gains from solar market participation. In the context of greater societal concern for broadening access to the benefits of the solar PV market, programs to expand access to financing for solar PV system purchases and to educate the public about the financial benefits of owning compared to leasing may be warranted.

CRediT authorship contribution statement

Christine L. Crago: Conceptualization, Methodology, Formal Analysis, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Emma Grazier:** Data Curation, Formal Analysis, Writing – original draft, Writing – review & editing, Visualization. **Dwayne Breger:** Conceptualization, Methodology, Formal Analysis, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Appendix

See Tables A.1 and A.2.

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