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Electricity bill savings and the role of energy efficiency improvements: A case study of residential solar adopters in the USA

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ABSTRACT

This study measures the *actual* value of electricity bill savings for residential solar adopters and examines how decisions related to the timing and type of energy-efficiency improvements affect a solar adopter's electricity bill savings. Among different types of efficiency upgrades, solar adopters with an efficient heating/cooling system and efficient lighting have higher savings than those without. Among solar adopters who made certain efficiency improvements, those who upgraded efficiency a few months before or after installing solar panels have higher savings than those who upgraded over three years before installing solar panels.

1. Introduction

Renewable energy is gaining importance in the residential sector across many states in the US. Emerging preferences for cleaner electricity as well as new technological advancements in distributed energy resources are the two major drivers for change. Among other types of technologies used to generate renewable energy onsite, solar panels or photovoltaics (PV) have become more practical for residential use.

Several studies have quantified the actual costs of residential solar PV installation [1–4]. However, studies that examine the private monetary benefits of residential PV are often based on estimations.[1] For instance, Lee et al. [8] examines the economic value of solar energy based on electricity generation simulated from RETScreen, a software developed by the government of Canada to assess the financial and technical feasibility of clean energy projects [9]. Borenstein [10] examines the private benefit of residential solar PV by using electricity usage data before and after PV installation along with a simulated solar generation to capture kilowatt hour (kWh) of electricity displaced. Similarly, Darghouth et al. [11] examine the private value of electricity bill savings by matching customer load data with the kilowatt hour (kWh) of electricity generated by a PV system sized to meet 75% of the load. The National Renewable Energy Laboratory (NREL)'s PVFORM/PVWatts Model [12] is used to simulate hourly solar generation in [10] and [11]. Likewise, several solar installers estimate a payback period or monthly electric bill savings based on pre-installation assumptions.

Such estimations can give us insight on the private benefits of solar adoption but it is not clear whether and under what conditions the estimated savings are realized. On one hand, simulations may overestimate savings due to underlying assumptions and other factors (e.g. ignoring rebound effects) [6]. On the other hand, engineering estimates may not fully capture favorable behavioral changes, such as reducing overall electricity consumption and shifting demand to times of peak generation [13], after PV installation. Therefore, it is important to measure *actual savings* from residential PV and examine how household choices and actions could affect savings.

Recent studies such as [10,11] and [14] examine factors that affect expected or estimated savings. These studies find that *estimated benefits* depend on the electricity market (retail rates and structures, compensation mechanisms) and volume of generation which in turn depends on the size and efficiency of solar panels as well as sunlight hours. According to the Office of Energy Efficiency and Renewable Energy [15], 'the amount of money a homeowner can save with solar depends upon electricity consumption, PV size and ownership, sunlight hours and the electricity market (rates, structure, and compensation mechanism).' While factors such as the weather and market conditions are beyond the control of individual homeowners, they could still benefit by adjusting their consumption and making conscious choice about the sizing and purchase of their PV system. Yet for residential solar adopters, it is still not well-understood which of these factors are relatively more important than others and to what extent [16].

The Office of Energy Efficiency and Renewable Energy [15] recommends 'energy efficiency upgrades and Energy Star appliances as a complement to solar energy' as both these investments contribute to the private benefit of residential PV. However, the *exact increase* in savings

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[1] Studies such as [5,6] and [7] explore the economic benefits of PV using measured data from residential buildings rather than estimates from simulations. These studies examine homes that are specifically built and designed as zero energy homes in order to examine scalability and feasibility.

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attributable to efficiency upgrades are not well understood. This is because of the lack of consistent evidence indicating private benefits in terms of direct energy savings with higher efficiency [5,17]. According to Berry and Davidson [6], more research is required to support minimum energy efficiency standards for residential buildings. In particular, solar adopters need transparent guidance on which types of efficiency upgrades to prioritize and when to accomplish these.

The objective of this study is to (1) measure the *actual value* of electricity bill savings for solar adopters in the US and (2) quantify the effect of household choices and actions on the value of savings, after controlling for electricity rates and location-specific factors. Among other factors, decisions related to the *timing* and *type* of energy efficiency improvements are shown to affect a solar adopter's electricity bill savings.

Survey data collected by the National Renewable Energy Laboratory (NREL) under the project entitled "Understanding the Evolution of Customer Motivations and Adoption Barriers in Residential Photovoltaic Markets" [18] is used to calculate the actual value of electricity bill savings for solar houses in a typical summer month. Factors that the Office of Energy Efficiency and Renewable Energy recommends as contributing to the value of savings [15] are empirically tested for a subset of solar houses covered in the survey. These factors are categorized into three: (1) Household choices and actions: PV size and PV ownership, investment in different types of energy efficiency improvements, and decisions related to the timing of each efficiency upgrade relative to time of PV installation; (2) Demographic characteristic of residents and the physical characteristic of the house; and (3) The retail price of electricity and other location-specific factors.

Section 2 presents the data source and description of methods. Section 3 outlines details on the measurement of variables and discusses findings from the survey data. Section 4 presents a discussion of regression results. Section 5 concludes with questions for future work.

2. Data and methods

The aforementioned survey data is collected from residential solar adopters located in New York, New Jersey, Arizona, and California [18]. The survey was collected between December 2014 and April 2015 from single-family and owner-occupied residential households. A few houses whose PV was not operating at the time of data collection are excluded from the analysis. In addition, this study only considers a subset of solar houses which installed PV during 2014–2015. This is to make the pre-PV and post-PV periods comparable. For instance, a household which installed its PV in 2001 faces different constraints compared to a household which recently installed PV (e.g. PV size, ownership model and costs have changed over the years). At the time of data collection, the houses considered in this study had relatively newer PV which have worked for not more than a year.

The sample size used in this study is 931 solar adopters. A majority of these (96.24%) installed their PV in 2014 while the rest were installed in 2015. About 88% of respondents indicated the reason for solar adoption as a means of lowering their electricity bill. Out of the 931 solar adopters in the sample, 96 are located in New Jersey, 144 in New York, 31 in Arizona, and the rest 660 in California. The average number of panels installed on each house is 36.63 panels (excluding 2 unusually high numbers). The system capacity factor in the sample ranges from 13% to 20% with an average of 17% (capacity factor is reported based on locale and kWh produced, averaged over the year) [18]. The average size of a house in the sample is 2074 square feet of living space, and the average age of a house is 41 years. A majority of the solar houses (78%) have leased their system.

Using responses from the survey data, a variable is constructed to measure the actual value of savings for solar adopters; this is used as a proxy for the private benefit of solar adoption. A multi-variable regression model is used to test and quantify the effect of the three categories of factors that are expected to determine a solar adopter's value of savings. The baseline regression equation is presented as Eq. (1.1) where sub-script i represents each solar adopter in the sample.

$$V_i = \beta_0 + \beta_1 PVsize_i + \beta_2 PVownership_i + \beta_3 Efficiency_i + \beta_4 Complement_i \\ \beta_5 Consumption_i + \beta_6 P_i + \beta_7 Location_i + \varepsilon_i \tag{1.1}$$

- V_i measures the value of electricity bill savings for each solar adopter i.
- $PVsize_i$ measures the size of PV.
- $PVownership_i$ identifies the chosen PV ownership model (i.e. purchase or lease).
- $Efficiency_i$ indicates whether household i has made energy efficiency upgrades or not.
- $Complement_i$ identifies solar adopters who consider solar energy and energy efficiency as complements (i.e. invest in both around the same time).
- $Consumption_i$ measures total monthly electricity consumption.
- P_i is the average retail electric rate paid by each solar adopter.
- $Location_i$ identifies specific locations (state, county, zip code) with more or less favorable environments (e.g. sunlight hours) for PV.

3. Measurement of variables and insights from the survey data

3.1. Measuring the value of electricity bill savings

Studies that estimate the value of electricity bill savings for the US residential sector include [10,11] and [14], all of which measure savings as dollars saved per kWh of (estimated) electricity generated by a PV. Borenstein [10] defines monthly electricity bill savings as the average price of electricity that would be purchased if not displaced by a household's PV. In a similar way Darghouth et al. [11] and [14] calculate electricity bill savings as the reduction in annual utility bill per total annual kWh of (estimated) electricity generated by the PV.

This study considers an alternative definition for the value of savings, one which does not rely on estimating solar generation. The value of electricity bill savings for each solar adopter (V_i) is calculated by subtracting the post-PV monthly electricity bill from the pre-PV monthly bill and expressing the difference as a ratio (or percentage) of the pre-PV electricity bill. This is calculated for a typical summer month where generation is expected to be the highest. This metrics assumes that electricity usage (and underlying determinants of usage such as weather conditions) across the two billing periods (pre- PV and post-PV) are fairly comparable.

A total of 678 solar houses have complete data to calculate the value of savings, and the discussion in this sub-section is based on these houses. The average monthly electricity bill for the sample is $258.43 in a typical summer pre-PV and $91.36 in a typical summer post-PV. The average value of savings is about 61%, which means a typical solar adopter's summer electricity bill is 61% lower post-PV compared to pre-PV. The average value of savings differs across states with Arizona having the highest average value of savings of 71% and New Jersey having the lowest average value of savings of 50%. Average savings for solar adopters in New York and California are 54% and 62% respectively.

The result in [10] indicates that in California PV adopters expect to reduce their monthly electricity bills between $0.213 and $0.272 for each kilowatt hour (kWh) of solar generation. This roughly translates into $142.71 to $182.24 monthly average savings for the average PV size considered in [10] (The average PV capacity for 2013 adopters is given as 4.8 kw in [10] and [12] is used to roughly replicate an estimated monthly generation of 670 kWh). The average solar adopter considered in this study saves $170.26, and adopters in California save on average $178.32 in a typical summer month. These amounts, although within range, are on the higher end of savings estimated in [10] because they are based on a typical month in summer.

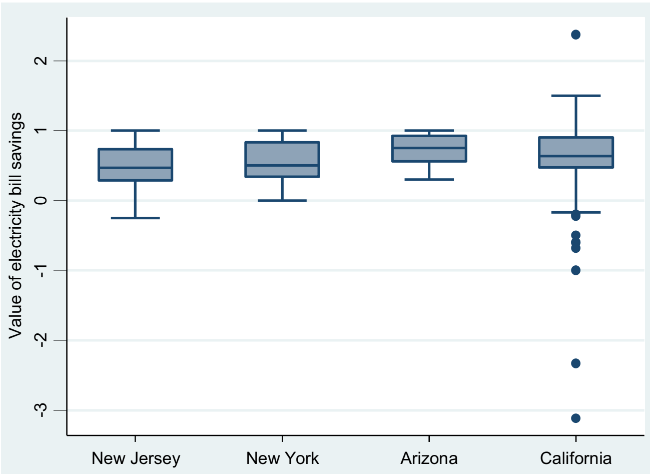

Fig. 1. Box-plot of value of savings across states. The y-axis measures the value of electricity bill savings as a ratio, and the x-axis presents the four states. Author's calculation based on data obtained from [18].

Generally, most of the households in the sample have between 0% and 100% savings except a few which have either over 100% value of savings (9 solar houses) or a negative savings (12 solar houses). A negative savings indicates that the solar adopter's post-PV electricity bill is higher than its pre-PV bill, and such houses appear to have fewer number of panels than the rest in the sample. These houses have 14 panels on average compared to 36 panels owned by the average solar house in the sample. However, the houses with a negative savings are not necessarily larger in floor area than the average solar house in the sample.

As Fig. 1 indicates, a majority of the houses with a negative savings are outliers in California. Among other factors, increase in electricity consumption post-PV (e.g. performing more energy intensive activities post-PV) could have contributed to a negative savings, but this could not be confirmed from the survey. All of the houses with a negative savings had their system leased from the same installer. A more likely reason for no savings could be the mismatch between generation and consumption. One respondent with a negative savings mentioned that the leasing model requires the household to pay for all solar energy generated by the system even when it was not consumed by the house.

On the other hand, houses with a greater than 100% savings appear to have several more panels than the average solar house in the sample. These houses are all located in California and all have a negative electricity bill post-PV suggesting that excess generation is sent back to the grid for some credit or compensation. These households probably have an oversized PV system.

3.2. PV size and ownership

Each solar adopter is faced with decisions regarding the size and ownership of the PV, given budget and other constraints. Although the decision on PV size is recommended by the installer depending on load profile and location factors, the household may have some discretion on how much of its energy demand it is willing and able to offset. The relationship between PV size and the value of savings, measured as a percent of pre-PV bill, is generally expected to be positive [15]. This is because lower solar generation is less likely to significantly reduce net consumption and more likely to decrease any compensation from net metering credits leading to lower value of savings (*Hypothesis 1:* $\beta_1 > 0$). In contrast, Darghouth et al. [14] find the value of bill savings, when measured in dollar per kWh of solar energy produced by the PV system, declines with PV size. This is because, as solar generation increases, the customer faces a progressively lower marginal price for its net consumption and thus receives progressively lower incremental bill savings. PV size in [14] is measured as a percentage of load the PV can offset.

To measure PV size, the number of panels per square foot of the living space of the house is calculated. This metrics assumes that fewer panels relative to the house size yields lower solar generation and represents smaller production capacity. A more preferred metrics is PV capacity in kW, but since about 65% of responses are missing, it will not be used in the analysis. Alternatively, as an additional measure for PV capacity, the system capacity factor measured as the kWh of generation per kW of capacity can be used. A higher capacity factor represents more favorable locational conditions and a higher production capacity.

Two PV ownership models are available for the sample, and these are either buying the PV or leasing it. The buying option requires the homeowner to make up-front payments (out of pocket or loan). A leasing option allows the household to enjoy lower electricity bills by making monthly lease payments with no upfront costs. A dummy variable is used to differentiate solar adopters who have bought a PV from those who lease: one for households who decided to buy and zero for those who chose to lease. About 22% of the households in the sample have purchased a PV while the remaining have leased. Among households who purchased a PV, about 44% reported that there was no option to lease (e.g. leasing not available, not offered by installer, or household did not qualify). Close to 76% of households who leased a PV disclosed that the option to buy was neither available nor offered by the installer. Thus, the leasing model appears to be the most accessible option for the majority of solar adopters considered in this study. For 83% of lessees, the lease is structured such that the household pays for the solar electricity generated by the PV in cents per kWh.

Solar adopters who purchase the PV have on average 84% value of savings while those who lease have 54% savings. This difference in the value of savings across the two ownership models is statistically significant at the 1% confidence level. The second hypothesis empirically tests whether such variation in the value of savings across the two PV ownership models is apparent *after* controlling for other relevant factors (*Hypothesis 2:* $\beta_2 \neq 0$).

3.3. Energy efficiency upgrades

Besides PV size and ownership, each solar adopter makes a decision regarding efficiency improvements in the house and timing relative to PV installation. According to the Office of Energy Efficiency and Renewable Energy [15], “energy efficiency upgrades complement solar energy economically.” An efficient solar house needs less electricity compared to a less efficient house with the same PV size and solar generation. Thus, efficient solar houses have lower net demand for electricity purchased from the grid, which increases the value of savings (*Hypothesis 3:* $\beta_3 > 0$).

The survey includes seven questions related to past improvements in energy-efficiency, and each household responds as having made those improvements or not. The efficiency upgrades are (1) improving the efficiency of the furnace, air conditioning system, or water heater; (2) installing efficient windows; (3) adding insulation; (4) weathering or air sealing the house; (5) sealing or insulating ducts; (6) installing efficient lighting; and (7) switching to Energy Star appliances.

About 77% and 73% of respondents have efficient appliances and efficient lighting respectively. These investments appear to be relatively less expensive compared to the rest. Close to 65% of solar houses in the sample have invested in an efficient furnace, air conditioning, or water heater. 58% have efficient windows, and 39% have added insulation. Only 26% and 24% of solar adopters weatherized/air-sealed and sealed/insulated ducts respectively.

If households invest in multiple efficiency upgrades, it is highly likely that these have prioritized investments in efficient lighting and/or Energy Star appliances (see Fig. 2). This makes sense as these two investments are relatively less expensive and may not require hiring contractors. Among the remaining capital-intensive home

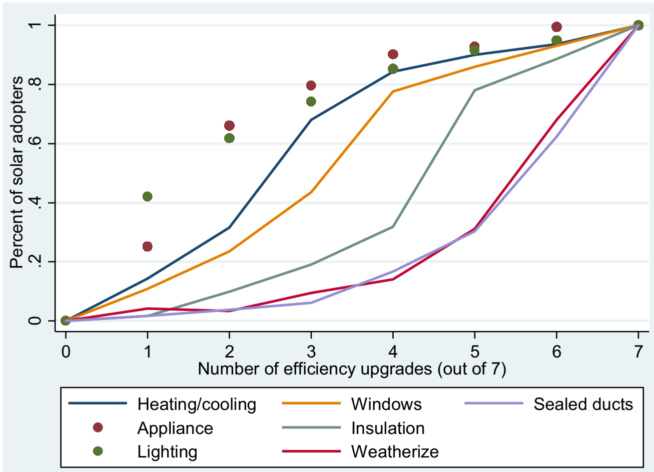

Fig. 2. Probability of adopting a given efficiency upgrade. The y-axis measures the percent of respondents with a given efficiency feature, and the x-axis measures the total number of efficiency upgrades.
Source: Author's calculation based on data obtained from [18].

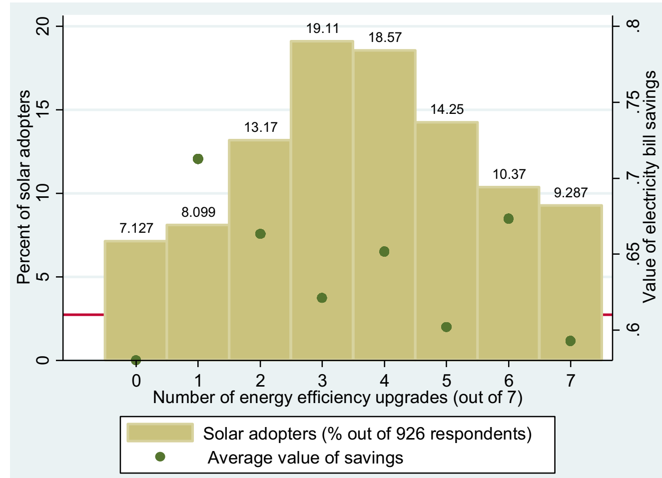

Fig. 4. Number of efficiency upgrades and value of savings. The primary y-axis measures the percent of respondents with a given number of efficiency upgrades, and the x-axis measures the total number of efficiency upgrades. The secondary y-axis measures the average value electricity bill savings as a ratio. Author's calculation based on data obtained from [18].

improvements, solar adopters prioritize investing in an efficient heating/cooling system (furnace, air conditioning, or water heater) followed by upgrading the efficiency of windows.

As Fig. 3 illustrates, only households who invested in efficient heating/cooling systems and efficient lighting have a higher than average value of savings. Other types of efficiency improvements do not yield higher than average savings. In fact, it is surprising that households who upgraded the efficiency of windows, weatherized, and insulated ducts have lower than average savings.

Among households with an efficient heating/cooling system close to 84% have at least one other type of efficiency upgrade. Similarly among households with efficient lighting, close to 78% have either weatherized or insulated the house, sealed ducts, or upgraded to more efficient windows. So one reason why households with an efficient heating/cooling system have higher than average savings could be because these are the same people with other types of efficiency upgrades.

Fig. 4 shows that households with none of the seven types of efficiency upgrades have the lowest value of savings. Households with only one type of efficiency upgrade appear to have, on average, the highest value of savings. Fig. 2 suggests that over 40% of solar adopters who have only one type of efficiency upgrade have most likely invested in efficient lighting, and a sub-set of these may be the ones who are enjoying the highest value of savings illustrated in Fig. 4. Therefore, having a single type of efficiency improvement may not necessarily be insufficient to increase the value of savings. Furthermore, prioritizing inexpensive investments in efficiency like having efficient lights may have higher private net benefits compared to other relatively more expensive investments.

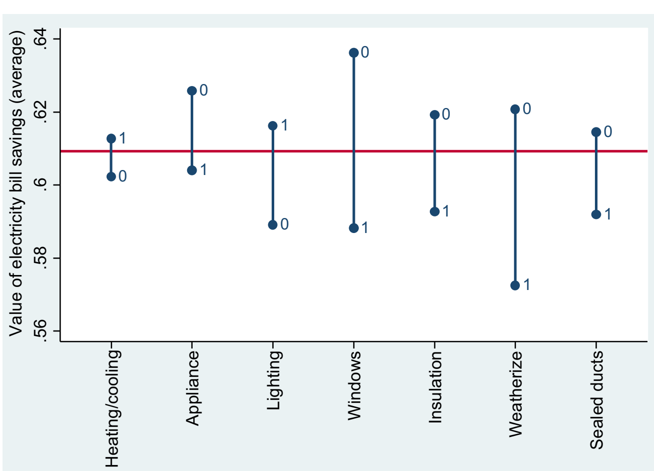

Fig. 3. Variation in savings across type of efficiency upgrade (1 stands for households with a given efficiency upgrade, and 0 represents households without the given efficient upgrade). The y-axis measures the average value of electricity bill savings as a ratio, and the x-axis indicates the type of efficiency upgrade.
Author's calculation based on data obtained from [18].

For the first five types of efficiency improvements, households report on the time (month and year) of upgrade, and using these responses, one can measure how far apart the two investments, PV installation and efficiency upgrade, are made. The average time gap between efficiency improvement and subsequent PV installation is 4–6 years.

Fig. 5 presents the distribution of solar adopters based on when one invested in efficiency relative to PV installation. Among houses with an efficient heating/cooling system, 47.3% made the upgrade over 3 years before the PV while 7%, 11%, and 15% made the upgrade 3–2 years, 2–1 years, and less than a year before the PV, respectively. About 19% of solar adopters with an efficient heating/cooling system made the upgrade with or immediately after the PV installation. Fig. 5 indicates that between 14% and 35% of solar adopters with efficient houses invested in a given efficiency upgrade with or immediately after the PV. Households who invested in efficiency closer to the time of (or with) PV installation may have done a conscious choice of viewing these two investments (PV and efficiency improvements) as complements in their objective to reduce monthly electricity bill. Compared to solar houses with efficiency upgrades farther away from the PV installation, houses with efficiency upgrades closer to the time of PV installation have a higher value of savings (*Hypothesis 4:* $\beta_4 > 0$).

3.4. House and resident characters

Electricity consumption affects the value of savings from solar [15]. Darghouth et al. [14] find that in California customers with high electricity usage have higher value of savings (per kWh of solar energy generated), keeping PV size constant. This is because high usage households are displacing more expensive electricity due to increasing block pricing. Likewise, the results in [10] suggest that the value of savings (for each kWh of solar generation) increases with electricity

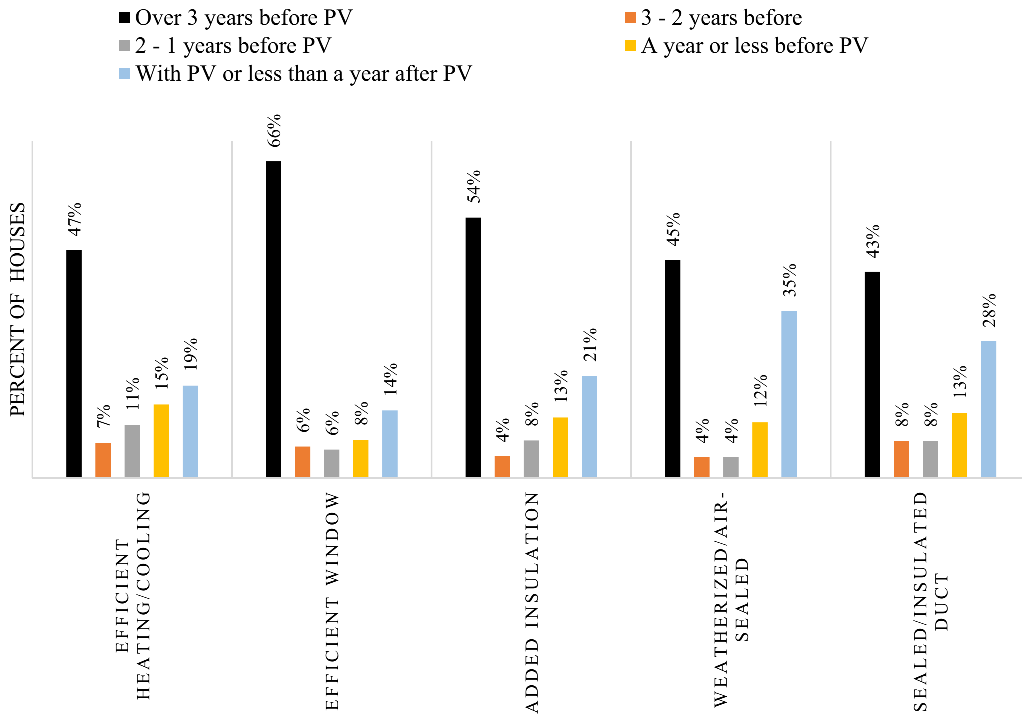

Fig. 5. Distribution of solar houses by timing of efficiency improvement. The y-axis measures the percent of solar houses, and the x-axis indicates the type of efficiency upgrade.
Author's calculation based on data obtained from [18].

usage.

Keeping other factors constant, a high-consuming household is expected to have a higher value of savings than a comparable house with lower consumption (*Hypothesis 5:* $\beta_5 > 0$). As there are no questions pertaining to monthly energy consumption in the survey, resident characteristics and house features are used as a proxy for electricity consumption. Jones et al. [19] present a review of several socio-economic factors and house features that affect residential electricity consumption. Among factors that are found to significantly affect electricity consumption include the age of the house (e.g. newer houses may have improved insulation and efficient appliances) and floor area [19,20]. Other factors are the presence of children (e.g. families with children use appliances more frequently or have additional electronics), income and education (due to correlation with house size and diverse range of appliance usage). In a similar study, Carlson et al. [20] find that US households with lower income generally have lower electricity consumption because of fewer appliances and smaller floor space. The timing of electricity demand relative to peak solar generation may also be affected by certain demographic variables [19]. For example, households who work outside the house have a different demand profile compared to retired households who stay home during the day. Kavousian et al. [21] find a significant correlation between the age of occupants and electricity usage in the US. The study [21] finds that households with individuals over 55 or between 19 and 35 years old recorded lower electricity consumption. This occurs because older individuals may be more conscious about electricity use and tend to use fewer electronics whereas individuals between 19 and 35 years old are more likely to be at work than at home during the day [21].

House size is measured in square feet of living space. The larger the house the higher is the electricity needed to cool during summer months. House age is also used as an additional control variable, and it is measured in number of years. The average house in the sample is 2074 square feet and is 41 years old. Two dummy variables, one which identifies retired respondents and the other which identifies households with children, are used as additional proxies for electricity consumption. About 35.36% of the respondents are retired whereas 33% of the households have children under the age of 18 living in the house. Household income and education are additional demographic characteristics used to control for other unobservable resident-specific factors that are likely to affect electricity consumption and other decision-makings. The respondents' highest education level completed and the annual household income are both measured in Likert scale (see Table 1). About 46% of the solar adopters have annual household incomes less than \$100,000%, and 44% have annual income between \$100,000 and \$200,000. About 43% of respondents do not have a bachelor's degree whereas the remaining have a bachelor's degree or higher.

3.5. Location specific factors

Location specific factors are generally assumed to be fixed or exogenous to the solar adopter's decision-making. For example, the solar adopter cannot influence the retail electric rate; one can only respond to the signal the price sends. The average county retail price of electricity is used as a proxy for the price of electricity. Data is available for the year 2013, which is a pre-PV year for the given sample of solar adopters. A higher retail price of electricity is expected to increase the pre-PV electricity bill; keeping other things constant, this will increase the value of savings (*Hypothesis 6:* $\beta_6 > 0$).

To control for other location-specific factors, dummy variables for states are added to Eq. (1.1). Finally, the total number of solar systems installed in the same zip code as a solar adopter is added in the regression. Solar houses located in areas of high solar penetration are expected to have higher value of savings (*Hypothesis 7*: $\beta_7 > 0$). This is because areas with several residential solar panels signal a more favorable economic, policy, and geographic environment for adoption of PV.

Table 1 presents descriptive statistics for the value of savings and all the independent variables.

Table 1
Descriptive statistics for solar adopters in the sample.

Variable	Unit of measurement	Observations	Mean	Standard deviation	Minimum	Maximum
Value of savings	Ratio of pre-PV bill	678	0.6093	0.3619	−3.11	2.37
Number of panels per living space	Number of panels per square foot	809	0.0156	0.1128	0	3.1578
System capacity factor	Percentage (or ratio)	928	0.1714	0.0184	0.1311	0.1997
Size of house	Square feet of living space	880	2074.18	738.80	430	10000
Children in the house	1 = yes, 0 = no	857	0.3302	0.4705	0	1
Respondent is retired	1 = yes, 0 = no	925	0.3556	0.4789	0	1
PV ownership	1 = purchased, 0 = leased	822	0.2202	0.4146	0	1
Respondent's highest education completed	Likert scale 1 (less than high school) to 8 (Doctorate)	919	4.5005	1.4848	1	8
Annual household income	Likert scale 1 (less than $25,000) to 9 ($400,000)	752	4.5173	1.5660	1	9
Age of the house	Years	924	41.48	21.45	1	188
Efficient heating/cooling system	1 = yes, 0 = no	926	0.6490	0.4775	0	1
Efficient appliance	1 = yes, 0 = no	926	0.7700	0.4211	0	1
Efficient lighting	1 = yes, 0 = no	926	0.7376	0.4402	0	1
Efficient windows	1 = yes, 0 = no	926	0.5832	0.4933	0	1
Added insulation	1 = yes, 0 = no	926	0.3974	0.4896	0	1
Weatherized or air-sealed home	1 = yes, 0 = no	926	0.2603	0.4390	0	1
Sealed or insulated ducts	1 = yes, 0 = no	926	0.2484	0.4323	0	1
Retail electricity rate	Average cents per kWh in 2013	928	17.33	4.14	11.67	27.86

4. Regression results and discussion

4.1. Factors affecting the value of savings

Several ordinary least squared (OLS) linear regressions are run to fit Eq. (1.1) to the data by including/excluding additional control variables; all of the regressions yield generally consistent estimates. Table 2 presents three representative results used to test all hypothesis except *Hypothesis 4*. The dependent variable is the value of savings for a typical summer monthly electricity bill. The value of electricity bill savings and the 2013 retail price of electricity are converted to logarithms to facilitate the interpretation of regression coefficients. Statistical significance is reported at the 1% and 5% levels as indicated by superscripts [a] and [b] respectively.

The regression analysis adjusts for heteroscedasticity by adopting techniques commonly used in the literature. Often times, survey data is collected using clustering, and such strategies may lead to the violation of the OLS- assumption that the error terms are independent of each other (e.g. households sampled in the same county may be more similar than households sampled at random). Moreover, each household in a given region (e.g. zip code, county) may have some unmeasured disturbances (e.g. location specific incentives, similar installer, etc.), and hence viewing each household as a cluster should yield more realistic standard errors. The standard errors reported in Table 2 are clustered by county to ensure accurate p-values. Robust standard errors are presented in parenthesis.

The Ramsey RESET test is performed after each regression to check whether any non-linear combinations of the independent variables may help explain the dependent variable. This test creates new variables based on the predictors and refits the model using those new variables to see if any of them would be statistically significant. The null hypothesis states that the model has no omitted variables. If the null hypothesis is rejected then the model suffers from misspecification, and it may be appropriate to fit the data using a polynomial or other non-

Table 2
Representative regression estimates for the value of electricity bill savings.

Independent variables	Coefficients (robust standard errors)	Coefficients (robust standard errors)	Coefficients (robust standard errors)
Number of panels per living space	0.0022 (0.0072)	0.0021 (0.0074)	0.0017 (0.0073)
System capacity factor			0.5874 (1.2985)
PV is purchased	0.1558[a] (0.0207)	0.1532[a] (0.0224)	0.1526[a] (0.0227)
Children in the house		−0.0025 (0.0207)	−0.0021 (0.0207)
Respondent is retired		−0.0060 (0.0325)	−0.0060 (0.0326)
Highest education completed	−0.0059 (0.0062)	−0.0031 (0.0068)	−0.0029 (0.0068)
Household income	0.0146[a] (0.0047)	0.0114 (0.0065)	0.0116 (0.0067)
Efficient heating/cooling system	0.0443[a] (0.0177)	0.0479[a] (0.0194)	0.0478[a] (0.0193)
Efficient appliance	−0.0204 (0.0172)	−0.0149 (0.0174)	−0.0153 (0.0177)
Efficient lighting	0.0366[b] (0.0185)	0.0364[b] (0.0192)	0.03612[b] (0.0192)
Efficient windows	−0.0019 (0.0160)	−0.0042 (0.0198)	−0.0038 (0.0199)
Added insulation	0.0294 (0.0304)	0.0212 (0.0293)	0.0218 (0.0288)
Weatherized or air-sealed home	−0.0018 (0.0285)	−0.0015 (0.0284)	−0.0006 (0.0286)
Sealed duct	−0.0787[b] (0.0364)	−0.0798[b] (0.0358)	−0.0803[b] (0.0355)
Size of house	−2.78e-06 (1.00e-05)	−1.61e-06 (1.1e-05)	−2.15e-06 (1.1e-05)
Age of house	−0.0003 (0.0005)	−0.0002 (0.0005)	−0.0002 (0.0005)
Number of PVs installed in zip code	2.3e-05 (4.6e-05)	1.00e-05 (5.0e-05)	1.00e05 (5.0e-05)
Retail electricity rate in 2013 (logarithms)	0.1165 (0.1007)	0.0751 (0.0976)	0.0799 (0.1001)
New York	0.0175 (0.0515)	0.0186 (0.0547)	0.0226 (0.0543)
Arizona	0.1061 (0.0634)	0.0995 (0.0677)	0.0724 (0.0785)
California	0.0347 (0.0431)	0.0448 (0.0470)	0.0218 (0.0674)
Constant	0.0321 (0.3055)	0.1340 (0.3056)	0.0377 (0.4177)
Observations	422	398	398
R^2	0.1588	0.1561	0.1564
F-stat	15.27[a]	11.75[a]	11.23[a]
VIF	1.42	1.42	2.01
Ramsey RESET F-stat	0.62	0.55	0.52

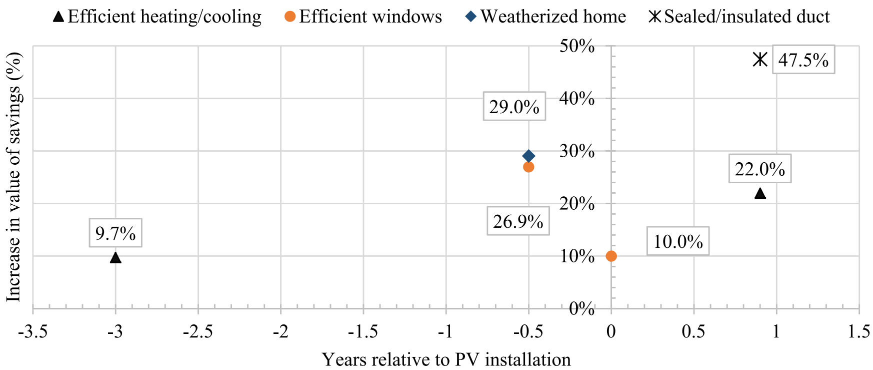

Fig. 6. Timing of efficiency and average impact on savings. The y-axis presents coefficient estimates from a linear regression which includes all independent variables, and the x-axis presents the time of efficiency upgrade relative to PV installation where minus sign indicates before PV and plus sign indicates after PV.
Author's calculation based on data obtained from [18].

linear functional forms. The test yields an F-statistics with a high p-value in all regressions, and hence there is no evidence to reject the null hypothesis. The variance inflation factor (VIF) test of multi-collinearity is performed where the value reveals by how much the variance of the estimated coefficients are inflated. The average VIF for the explanatory variables is lower than 2.5 indicating no concern for multi-collinearity.

A majority of the variables including PV size (measured by the number of panels per square foot and system capacity factor), electricity consumption (measured by square foot of the house, age of the house, availability of children and a retired respondent), and the variables used to control for location-specific factors are not statistically significant determinants of the value of savings for a typical solar adopter in the sample. Hence, there is no evidence that supports *Hypotheses 1, 5, 6,* and *7* for given the sample. The variable 'household income' initially appears to have a positive correlation with the value of savings, however, this correlation disappears once additional demographic characters ('children in the house' and 'retired respondent') are added to the regression.

The findings presented in Table 2 are in contrast to Borenstein [10], who finds that the range of savings (per kWh of solar generation) for solar adopters in California depends on electricity consumption and PV size which are shown to be correlated with household income. Furthermore, Darghouth et al. [14]'s main findings suggest that electricity market conditions and retail rate structures are the major determinants for the value of electricity bill savings for residential PV. The results from Table 2 indicate that household choices on efficiency upgrades matter for the value of savings.

Households with an efficient heating/cooling system have on average 4.5–4.9% higher value of summer savings compared to houses which do not have an efficient heating/cooling system. Similarly, houses with efficient lighting have on average 3.7% higher savings compared to houses which do not have efficient lighting. These provide *some* support for *Hypothesis 3*. However, it appears that houses with sealed ducts have on average 7.7% *lower* savings at the 5% significance level. Households who purchased a PV have on average about 16.6% higher value of savings than households who leased a PV. This concurs with *Hypothesis 2*.

Since the *availability* of two types of efficiency upgrades, namely an efficient heating/cooling system and an efficient lighting, are found to be positively correlated to the value of savings in electricity bill, households considering PV as a future investment could prioritize these upgrades before other types of efficiency improvements.

4.2. Complementarity between solar and energy efficiency

Regressions presented in the last column of Table 2 are repeated by replacing each of the five variables indicating the availability of an efficiency improvement (heating/cooling system, windows, insulation, weatherization, and sealed duct) by the timing of the upgrade with respect to the PV installation. The purpose is to test for *Hypothesis 4*.

That is, instead of using each of the five dummy variables controlling for the *availability* of an efficiency feature, eight dummy variables representing how long ago (months and years) the household invested in a given efficiency are used. The eight dummy variables representing the timing of a given efficiency improvement with respect to PV installation are as follows: efficiency improvement made (1) over three years before PV, (2) three years before PV, (3) two years before PV, (4) one year before PV, (5) the year PV was installed, (6) six months after PV, (7) nine months after PV, and (8) twelve months after PV. The first dummy variable is excluded from the regressions and used as a benchmark against which changes in the value of savings are measured.

Five different regressions are run, each for the five different efficiency upgrades, and the coefficient on each of the eight dummy variables are examined to identify statistical significance. Resulting regressions are based on a sub-sample of solar adopters who have a given efficiency feature; solar adopters without an efficiency upgrade are excluded. This approach measures the role of *timing* of the efficiency improvement for solar adopters who already have efficient houses.

Households who invested in efficiency not more than 3 years before their PV are assumed to view these two investments (efficiency upgrade and PV installation) as complements in the objective of generating savings. For such households, the *additional increase* in the value of savings due to investing in efficiency at a time closer to the PV investment than further away from the PV investment (further away means over 3 years before PV was installed) is measured. If the regression coefficient on a dummy variable measuring timing of efficiency improvement is positive, it is interpreted as follows: relative to houses with efficiency improvement over 3 years ago, those who improved efficiency at a given year before/after the PV have a higher value of savings in electricity bill, after controlling for other factors.

Results are summarized in Fig. 6. The figure presents regression coefficients with p-values 0.05 or less. Generally, results suggest that a solar adopter who invests in efficiency upgrades within three years before/after PV installation is expected to have, on average, higher value of electricity bill savings compared to solar adopters who upgraded efficiency over three years before PV. For the sample considered in this study, there is a fairly substantial degree of complementarity between residential PV and efficiency upgrades in the objective to maximize savings in electricity bill.

Further results indicate that the highest increase in the value of savings (47.5% additional savings) is achieved for households which have sealed or insulated ducts nine months *after* the PV installation. Thus, when considering the *availability* of sealed ducts, those houses without sealed ducts have higher savings than houses with sealed ducts. However, among houses with sealed ducts, those who sealed ducts a few months post-PV enjoy higher savings relative to the ones that sealed ducts over 3 years ago. Similarly, among solar adopter who weatherized their home in the past, those who weatherized six months pre-PV are expected to have 29% higher savings compared to the ones who weatherized over three years pre-PV.

Table 2 indicates that having an efficient heating/cooling system increases savings than not having it. Furthermore, Fig. 6 indicates that even more savings can be realized by investing in an efficient heating/cooling system closer to the time of PV installation than further before the PV. Households who invested in an efficient heating/cooling system three years before the PV realized 9.7% more savings than households who invested over three years before PV. In addition, households who invested in an efficient heating/cooling system about nine months after PV enjoyed 22% more savings than those who improved over three years before PV. Thus, investing in an efficient heating/cooling system closer to the year of PV installation, in particular investing a few months after PV, can help households realize more savings.

Among solar adopters with efficient windows, those who invested in efficient windows a few months before the PV installation or at the time of PV installation have a statistically higher value of savings compared to households which made those upgrades over three years before pre-PV. Specifically, solar adopters who invested in efficient windows six months before the PV are expected to experience 27% more savings whereas solar adopters who invested in efficient windows at the time of PV installation are expected to experience 10% more savings.

5. Conclusion

Understanding what affects a solar adopter's electricity bill savings and to what extent will benefit programs aimed at boosting solar adoption among targeted communities. For example, installers can design effective marketing techniques and ownership models to sell panels. This paper illustrates that policy makers who wish to maximize program impact should focus on PV ownership rather than lease. Similarly, households considering solar energy should carefully study the terms of third-party ownership models. Leasing options may be attractive due to low or no upfront costs; however, their net cost may be higher in the long-run.

The evidence presented in this paper suggests that a simple switch to an efficient lighting can help solar adopters offset a modest portion of their electricity bill. Such savings could translate into higher net private benefits for solar adopters. Furthermore, the evidence suggests that even investing in a single efficiency upgrade (before performing multiple efficiency upgrades) may lead to a substantial reduction in electricity bills. Thus, from a broader perspective, directing research and development towards boosting the efficiency of existing technologies, such as increasing the efficiency of the light bulb or making heat-pumps ultra-efficient, may be a more cost-effective strategy.

Among relatively more expensive efficiency upgrades, solar adopters ought to prioritize investing in an efficient heating/cooling system. Solar adopters who upgraded the efficiency of their heating/cooling systems have about 4.8% higher value of savings than those who have not made such upgrades in the past. The findings presented in this paper indicate that upgrading the heating/cooling system of a solar house generates the highest value of electricity bill savings when the upgrade is done a few months *after* the PV installation.

Other types of investments like having efficient windows, additional insulation, weatherizing and insulating ducts do not necessarily generate higher savings compared to houses without such improvements. However, among a sub-set of solar houses with some efficiency improvements, those with improvements made within a few months of installing PV have on average higher savings compared to those with improvements made over three years before the PV. In particular, for the sample considered in this study, the findings imply that potential solar adopters considering to invest in efficiency could get a higher savings with one or more of the following decisions: (1) switching to a more efficiency heating/cooling system a few months *after* PV installation, (2) sealing ducts a few months *after* PV installation, (3) switching to more efficient windows a few months *before* PV installation, and (4) weatherizing the house a few months *before* PV installation.

The evidence from this study suggests that variables commonly believed to affect electricity bill savings do not necessarily matter for the subset of solar households considered. For example, after controlling for household-specific decisions like efficiency choices and PV ownership, the location of a solar house in Arizona or New York has no effect on summer savings. Furthermore, even within a given state, being located in zip codes with several other solar houses may signal favorable conditions for solar adoption but does not necessarily signal favorable conditions for higher electricity bill savings from solar energy. Given the limitations of the data, no evidence was found for the effect of the average retail electric rates on the value of savings. Future studies are needed to examine whether more realistic electric rate structures (e.g. time of use rates, demand charges) affect the value of savings.

The survey used in this study was collected with the purpose of understanding the barriers and motivation for the adoption of residential PV. More surveys and datasets are needed with the specific objective of comprehensively measuring and understanding the actual electricity bill savings of solar adopters. For example, with advanced and smart metering devices, hourly usage, solar generation, and the amount of power sent back to the grid can be measured for the entire year. In this way, the value of savings in electricity bill will be more complete.

According to Herche [12], the complex interaction between renewable technologies and corresponding markets, such as the PV market, pose difficulties for policy makers. Informed policy-making requires a deeper understanding of the variation in the private monetary benefits of renewable energy adoption. The approaches adopted in this study provide some initial inputs that can further be investigated to provide comprehensive evidence-based strategies that are likely to be associated with higher savings. Furthermore, with a better understanding of the extent of complementarily between solar energy and energy efficiency, states can adopt effective policies aimed at encouraging energy efficiency and renewable energy.

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