Renewable Energy 89 (2016) 498–505

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Overcoming barriers and uncertainties in the adoption of residential solar PV

Varun Rai [a, b, *], D. Cale Reeves [a], Robert Margolis [c]

[a] LBJ School of Public Affairs, The University of Texas at Austin, USA
[b] Mechanical Engineering Department, The University of Texas at Austin, USA
[c] National Renewable Energy Laboratory, Washington D.C, USA

ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form
18 November 2015
Accepted 29 November 2015
Available online 23 December 2015

Keywords:
Solar photovoltaic (PV)
Information channels
Peer effects
Consumer behavior
Leasing
Individual decision-making

ABSTRACT

In recent years decreasing hardware costs have driven down the installed price of solar photovoltaic (PV) systems and spurred adoption. However, system cost is not the only barrier faced by solar adopters. Potential adopters also face various informational barriers, leading to high indirect costs during the information search process. There is a significant gap in the literature for empirical work on solar adoption linking how the information context (installer marketing; neighbors with solar, i.e., peer effects; etc.) interacts with a potential adopter's motivations to impact decision outcomes. To address this gap we present results of a new survey on the decision-making process of residential PV adopters in northern California. The main aspects of our analysis include: salient motivating factors, information gathering process, peer effects, role of installers, and factors driving the choice of outright purchase versus third-party ownership (e.g., leasing) modes of adoption. We find that installers and neighbors play important, but often supplementary, roles throughout the decision-making process and have influence on both the decision to adopt as well as on the mode of adoption. Furthermore, expected financial returns and concerns about operations and maintenance are the main determining factors for the mode of adoption.

1. Introduction

Stabilizing global CO_2 emissions to avoid catastrophic climate change while meeting the increasing global demand for energy will require drawing on a variety of methods, including significantly scaling up the use of solar photovoltaic (PV) generation [1]. Potential to scale up solar PV generation exists at both the utility level [2] and at the residential level [3], on which this work focuses. Decreasing hardware costs combined with policy support in the form of federal, state, and local incentives [4–7] is driving down installed prices of solar PV systems, thereby spurring demand [8]. However, system cost is not the only barrier faced by solar adopters; potential adopters also face various informational barriers, leading to high non-monetary (i.e., indirect) costs during the information search process, which can be quite intensive for a capital-intensive durable like a solar PV system [9,10]. Furthermore, novelty of the technology combined with expectations of rapid technology improvement and cost reductions accentuate the real options (i.e., “wait and watch”) problem for technologies likes solar PV [11]. Addressing these barriers requires a better understanding of the household decision-making process associated with the adoption of capital-intensive consumer energy technologies.

The literature on residential solar adoption [9,10,12–19], while growing, is still in early stages. In particular, there is a significant gap in empirical work on solar adoption linking how the information context (installer marketing; neighbors with solar, i.e., peer effects; information from utilities; etc.) interacts with a potential adopter's motivations to impact decision outcomes such as the duration of the decision period and the mode of adoption (for example, buy or lease). Addressing these questions could provide insights for addressing barriers to solar adoption more effectively and for improving the effectiveness and efficiency of utility solar programs more generally.

This paper seeks to contribute to the body of growing literature focusing on the design of policies and programs to speed the diffusion of novel consumer energy technologies. To that end, we analyze the results of a new survey on the decision-making process

* Corresponding author. 2315 Red River St., The University of Texas at Austin, Austin, TX 78712, USA.
E-mail address: raivarun@utexas.edu (V. Rai).

http://dx.doi.org/10.1016/j.renene.2015.11.080
0960-1481/

of residential PV adopters in northern California, with a particular focus on adopters' information-search process and how it impacts the ultimate mode of acquisition (buy or lease) by overcoming barriers and uncertainties with PV adoption. Accordingly, we focus on identifying factors that initiate the decision-making process, are important during it, and inform the mode of final adoption.

2. Related literature

Information and the costs of acquiring it are central to understanding individual decision-making [20,21]. The main function that information plays is in enabling economic agents to calculate benefits and costs (to assess relative utilities) of decision alternatives. Behavioral factors (such as risk aversion, anchoring, decision heuristics, etc.) and social factors (such as norms, trust-based information networks, etc.) are of special interest because of the way they expose different individuals to different sets of information [15,21–24], thereby giving rise to the bounded rationality of individual decision-makers [21]. As such, an important question is: how and from whom do individual decision-makers seek the necessary information and form expectations about technological trajectories[1] to aid their decision-making? We address this question in the context of residential solar PV adoption process.

From their initial exposure to solar through the final decision to adopt, adopters of solar PV use information gathered from a variety of sources to reduce the uncertainties associated with adopting solar [21,25–27]. Recent work has explored the role of peer effects [10,28], uncertainty [19], business models [8,12,18,29], electricity rates [13,30], and discount rates [12,18] in residential solar adoption and found a linkage between factors in the decision-making process (such as motivations to adopt, perceived uncertainties, sources of information, etc.) and the mode of acquisition – buying outright or leasing [10,13,17]. Importantly, certain contexts modify the informational requirements. For example, Rai & Robinson [10] find that peer effects (the influence of one's neighbors) decrease the duration of the adoption decision period; peer effects are interpreted as a pathway that provides valuable information to potential adopters that helps reduce uncertainties inherent in adopting an emerging technology like PV.

Uncertainties about technological performance are an important driver for the choice of adoption mode: buying versus leasing. Drury et al. [13] posit three characteristics that explain the increasing trend toward third-party ownership (TPO), which includes leasing and power purchase agreements (PPA), of residential solar PV in California: it reduces the upfront financial burden – both overnight costs and costs associated with securing financing; it removes some of the complexities and uncertainties associated with adopting a new technology; and it re-frames the financial benefits of adoption as a simple-to-perceive monthly savings. Using more nuanced household-level survey data, Rai & Sigrin [18] find a similar market-expanding effect for TPO – specifically leasing – in the Texas market. However, in contrast to Drury et al. [13], they do not find a demographic difference between adopters that pursue leasing and those that buy outright. Instead, they find that leasing is preferred by customers who have a tighter cash flow situation: the individual-level discount rate of lessees was 8–21% points higher than those who bought their PV system. Accordingly, Rai & Sigrin concluded that in the early phases in a market the TPO model is able to penetrate the "information-ready but cash-poor" market segments [18].

While the literature has begun to empirically address the behavioral drivers and information processes involved in customer decision-making in solar adoption, much of the current work aggregates household-level heterogeneity. Understanding household-level heterogeneity is important for estimating demand [31], for building detailed spatio-temporal models of adoption [32–34], and for identifying and addressing information gaps and other barriers faced by different customer segments [16]. In this paper we analyze a new household-level dataset from a survey of residential solar PV adopters to specifically address the following questions: (i) what are the salient motivational factors that drive households to consider solar in the first place, (ii) where do potential adopters get their information from during the research (i.e., information gathering) period, and especially what is the role of peer effects and installers (i.e., the supply side) in this process, and (iii) what drives the decision to buy versus lease solar?

3. Data and methodology

The analysis in this paper uses a dataset composed of a survey of households that chose to adopt solar PV systems. As explained below, the survey data is further augmented with utility solar program data on those systems. Between April and June of 2014, a survey was conducted of residential customers in northern California who had completed installing solar PV systems. The goal of the survey was to characterize the decision-making process undertaken by PV adopters. The survey was sent to 2131 customers, of which a total of 380 completed responses were received (18% response rate). Section 4.1 and Supplemental Information (SI) provide more detailed description of the sample.

The survey collected information from respondents across eight broad categories: system details, purchase/leasing/power purchase agreement (PPA) details, decision-making process, financial aspects, sources of information, post-installation evaluation compared to prior expectations, environmental attitude, and demographics. There were a total of 57 questions distributed across the eight categories, resulting in 206 individual variables.[2] These data are matched by customer to the solar program dataset, which contains system-level details of the individual PV systems such as nameplate capacity, date of interconnection, total system cost, and rebate received. Most survey respondents (97%) were successfully matched to corresponding system-level data in the program dataset.

The analysis in this paper focuses on adopters' decision-making process – the process that PV adopters went through when deciding to adopt solar. The main aspects of our analysis include: salient motivating factors ("spark events"); information gathering process; role of installers; and factors driving the choice of buy versus third-party ownership (TPO) modes of adoption (i.e., lease or PPA). We use two methodological approaches to conduct the analysis. First, we use simple descriptive statistics: Fishers Exact test for independence and contingency tables to explore the demographics of the sample, the methods of acquisition employed by respondents, and their responses to questions relevant to their decision-making process. Unless otherwise noted, only results of tests that are significant at $\alpha = 0.05$ are presented. Second, we use a multivariate econometric model to identify determinants of the

[1] In the case when the decision involves the adoption (or not) of new technologies, an important consideration is the agents' expectations about the future technological trajectory, i.e., how the cost-quality frontier of the technology will evolve over time. A common assumption in the literature is that of rational expectations, which assumes agents' expectations to be the same as the actual market outcome (see Dubé et al., 2014 for more discussion on this issue). This can be problematic for new technologies, for which there is little past experience or data to form such expectations upon [38].

[2] A full table of relevant survey results is presented in SI-1.

mode of ownership.

4. Results

4.1. Description of the sample

The respondents in the sample are, in a general sense, wealthy, educated, and relatively older (median age 62 years). Supplementary Information-2 (SI) provides additional details on respondent demographics. Median nameplate capacity among respondents is 4.7 kW, slightly lower than the national median system size between 2010 and 2012 [8]. The majority (57%) of the PV systems in the sample came online after 2012, and 96% were installed after 2009. SI-3 provides details on installed system prices. Many (201, 53%[3]) respondents report that there were no PV systems in their neighborhood (defined in the survey and for this analysis as "a radius of roughly 5–10 blocks" around a respondent's house) during their decision period to adopt solar. Access (or lack thereof) to neighbor peer effects splits the respondent sample in two: those with or without existing PV systems in the neighborhood. Throughout the rest of this analysis, various decision-making factors are considered contingent on whether or not solar PV systems were previously installed in a respondent's neighborhood when they began their decision-making process.

4.1.1. Methods of acquisition

Three methods of acquisition are studied in the survey: outright purchase (i.e., "buying"), leasing, and entering into a solar PPA. Respondents were asked to indicate which options were available to them when they decided to install a system. Over the entire sample (N = 380), nearly all respondents (332, 87%) had the option to buy a system, fewer reported having the option to lease (213, 56%), and fewer still reported having the option to enter a PPA (115, 30%). Respondents only begin to report the availability of TPO options in 2009, which is when TPO became increasing significantly across California. Fig. 1 shows how *availability* of the three options was distributed across the three options for the respondents. Additional details on changes in the availability and the actual methods of adoption over time are provided in the SI-4.

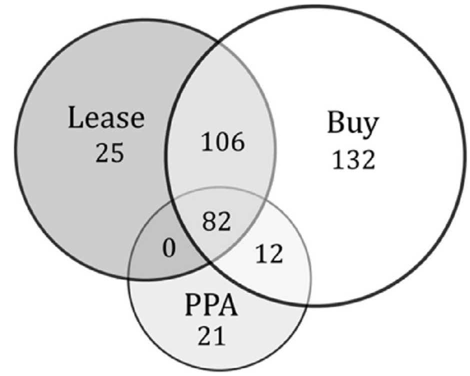

Fig. 1. Distribution of availability of methods of acquisition over N = 378 respondents that provided valid responses. Buying the PV system outright is the most common method of acquisition in the sample. More than half of the respondents report purchasing their system outright (226), compared to those that report leasing (98) or entering into a solar PPA (54). Given that a respondent had at least one option in addition to buying, 81% chose to buy. Similarly, 63% of those that had at least one option in addition to leasing chose to lease and 61% of those that had at least one option in addition to PPA chose to PPA. Of the 106 with the option to buy and lease 43% buy; of the 12 with the option to buy and enter a PPA 60% buy; and of the 82 will all options available 43% buy, 20% lease, and 37% enter a PPA.

4.2. Initiating and sustaining the decision-making period

4.2.1. Spark events

Respondents reported which of a selection of situations or events prompted their initial interest in installing their solar PV system. Throughout this analysis, we will refer to these as "spark events" because they sparked the initial interest in a respondent to install solar. Respondents were free to choose more than one spark event from the list shown in Table 1, including a write-in response for "Other."

Direct marketing by a solar company was the most popular spark event, followed closely by planning for retirement and a recent increase in electricity rates. These three spark events each operated on roughly 30% of the respondents.[4] Comparatively, both of the two neighbor-related spark events "seeing a neighbor install solar panels" and "conversation with a neighbor who had solar panels" combined only sparked less than 15% of the respondents. However, looked at alone this metric underestimates the prevalence of neighbor-related spark events. One really needs to look at this metric *conditional* upon a respondent having access to a neighbor with solar PV already installed. Of the subset of respondents that report having at least one solar PV system in their neighborhood (170), 27 reported their interest was sparked by seeing a neighbor install a system (16%), 26 report that their interest started after a conversation with a neighbor (15%), and 12 (7%) report that their interest was sparked by both seeing a neighbor install a system and having a conversation with a neighbor. Thus, conditional upon access to neighborhood peer effects, the two neighbor-related spark events combined are nearly as common as direct marketing, retirement planning, and increasing electricity rates. Fig. 2 illustrates the importance of spark events conditional on access to neighbors with solar PV.

Fisher's exact test reveals no significant relationships between spark events and methods of acquisition eventually chosen by the respondents, with the exception of when respondents' interest is sparked by a conversation with a solar company at a retail store (n = 34; 9% of the respondents). Respondents reporting this spark event enter into a PPA twice as frequently as expected under independence.

4.2.2. Co-adoption

Respondents reported any energy related products, other than their PV systems, that they had either already adopted or were considering adopting, along with the timing of any previous adoption relative to the installation of their PV systems. The majority of respondents (313, 82%) either co-adopted another energy-related product or were considering an adoption (see SI-5 for full details on co-adoption responses). Over half (208, 55%) adopted another energy product before adopting solar PV, 67 (18%) co-adopted simultaneously with solar PV, and 100 (26%) adopted afterwards.[5] The greatest interest in co-adoption – including both realized and planned adoptions – was in major energy efficiency

[3] Frequently throughout this paper, results will be presented in this format: (201, 53%). Within the parentheses the count of observations meeting the specified criteria is presented first, followed by the percentage of observations meeting the specified criteria compared to the relevant larger group.

[4] Although there was overlap between the three main spark-event groups, the only significant dependence is a positive relationship between the retirement and increased electricity rates spark events.

[5] These figures consider respondents that co-adopt or plan to co-adopt at least one of several products asked about in the survey, as such, individual respondents may be counted multiple times in this break-down. For a complete report of individual co-adoptions, see SI-5.

Table 1
Survey response choices for situations or events that prompted respondents' initial interest in installing their solar PV system.

- Planning a remodeling or building project
- A recent increase in electricity rates
- Thinking about retirement planning
- Seeing a neighbor install solar panels
- A conversation with a neighbor who had solar panels
- A conversation with a friend, coworker or family member who had solar panels
- A conversation with a solar homeowner as part of a home tour
- A conversation with a solar company at a retail store (Home Depot, Costco) Other
- A radio or television advertisement
- Direct marketing by a solar company (salesman visit, mailer or door hanger)

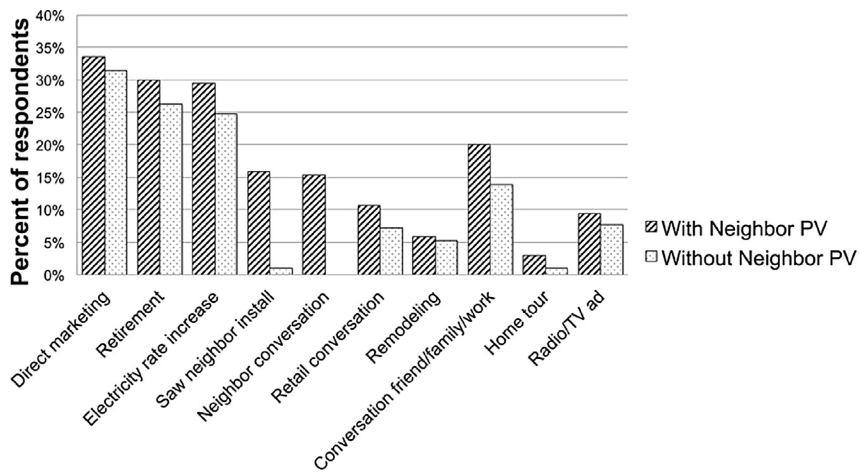

Fig. 2. Reported spark events — events that evoke initial interest in installing solar — separated by respondents who have access to neighborhood peer effects (left hand columns), and those that do not (right hand columns). The main difference between these two groups is the neighborhood peer-effect itself: saw neighbor install (="seeing a neighbor install solar panels") and neighbor conversation (= "conversation with a neighbor who had solar panels"). All other differences are statistically insignificant. Although respondents with neighborhood PV report conversations with friends, family, and co-workers as a spark event more frequently than those without neighborhood PV, the relationship is not significant ($p = 0.167$).

improvements, followed by smart thermostats and hybrid vehicles: 36% (138) had already adopted energy efficiency improvements and another 11% (43) were planning to do so. The most popular actual (i.e., realized) co-adoptions, both as precursors to and simultaneous with solar PV adoption, were new roofing, smart thermostats, and efficiency improvements. Looking forward, more respondents reported currently considering purchasing a plug-in electric vehicle (55, 14%) than any other technology, followed by electric vehicle charging stations (50, 13%). Thus adopters are not considering installing PV systems as a stand-alone decision; their decisions are likely influenced by other recently adopted energy-related technologies and appears to be part of a larger home improvement plan. This finding has important implications for studies that try to estimate the effect of solar installations on home value or on electricity consumption. Specifically, our findings suggest that such studies will need to control (account) for any other energy-related investment made by solar-adopting households at or around the time of solar installation. Unless that is done, such studies will likely overestimate the beneficial effects of solar adoption on home value, and the estimation of the effect on electricity consumption will also be biased.

4.2.3. Information pathways

4.2.3.1. Importance of information sources. Respondents were asked to rate *the importance of information* from a set of sources in their decision to install a PV system by answering several five-point Likert items with the possible responses "Not important at all," "Not very important," "Moderately important," "Very important," and "Extremely important." The set of sources is shown in Table 2, but also included a write-in response for "Other".

The median response for "Solar installers" was "Very important." Information from utilities and online resources was "Moderately important," while information from other sources was either "Not very important" or "Not important at all." Respondents that become interested through (i.e., sparked by) direct marketing rate the importance of information from acquaintances as "not important at all" with greater frequency than expected. This suggests that those whose spark event is direct marketing (by solar installers) are able to meet their information requirements without seeking information from other sources, likely because installers are able to meet the information needs of this group. Viewed differently, solar installers, for whom direct marketing represents a relatively expensive way to get customers' attention, appear to be successfully shepherding these hard-won customers through the decision-making process. Overall, respondents feel strongly that interactions with their solar contractor improved the quality of their information, motivated them, and gave them confidence to install solar.

4.2.3.2. Role of peer effects. The importance of information sources also depends upon the level of accessibility of different types of

Table 2
Information sources in PV adoption decision-making.

• Coworkers	• Neighbors
• Members of online forum(s)	• Local non-profit groups
• Online resources	• Acquaintances
• Roofing contractors	• Family
• Solar installers	• Local utility

Table 3
Survey questions addressing the impact of interactions with other solar PV owners on the respondent's PV adoption decision.

Q1	Talking to owners of solar systems was useful or would have been useful
Q2	I would have liked to talk to more solar owners, but couldn't find any
Q3	Solar systems in the neighborhood motivated me to seriously consider installing one
Q4	Without the solar systems in my neighborhood, I would not have installed a solar system

information channels to the respondents. For example, adopters who had access to neighbor-related peer effects[6] when they began their decision-making process or those that report a neighbor-related spark event rate information from neighbors and from members of online forums as "very important," more than expected under independence. Further, those that report a neighbor-related spark event also value information from acquaintances more than expected. These findings suggest that neighborhood peer effects provide valuable information to potential adopters and that those potential adopters who experience such peer effects also find valuable information through acquaintances and online forums – also relational forms for information channels, just like peer effects themselves.

Respondents also directly evaluated the usefulness, availability, and importance of contact with other solar owners as they made their decision to install solar PV by answering a series of five-point Likert items ranging from "strongly disagree" to "strongly agree" questions shown in Table 3.

Of the 270 respondents that answered question one (Q1), a majority (194, 72%) agreed or strongly agreed that talking to other owners was or would have been useful, 116 (43%) also reported that they actually contacted another PV owner, and 42 (16%) reported that they contacted a PV-owning neighbor. Additionally, of the 282 respondents that answered question two (Q2), nearly half (132, 47%) agreed or strongly agreed that they would have liked to talk to more solar owners but couldn't find any; not surprisingly, this group reports 0.22 (p-value: < 0.01) fewer systems in the neighborhood than those that disagreed or neither agreed nor disagreed.

Of the 170 respondents that had pre-existing PV systems in their neighborhoods, 49 (29%) agreed or strongly agreed that "Solar systems in the neighborhood motivated me to seriously consider installing one." Twenty-two of these 170 respondents (13%) further recognized the importance of neighbors as information pathways in their decision by agreeing or strongly agreeing that without PV systems in their neighborhood they would not have chosen to install. Thus peer effects impacted the decision-making of about 30% of the respondents and fully determined the behavior of 13% (who would not have adopted solar otherwise). This is telling about the scale of importance of peer effects in solar adoption, given that perception of peer influence on behavior is typically underreported [35]. Consistent with the literature on peer effects in solar adoption [10,25], overall, these findings strongly suggest that neighborhood-level peer effects play a significant role in providing valuable information to potential adopters of solar. However, the majority (87%) of these 170 respondents disagree that they would not have installed solar PV systems had there been no previously installed PV systems in their neighborhood. Thus while the respondents acknowledge the influence of peer effects in their decision to install PV, they believe that they would still have eventually installed solar even with the lack of peer effects. This suggests that peer effects, at least *as perceived by adopters*, is a facilitating mechanism by providing useful direct or indirect information which translates into a higher motivation and confidence to adopter, but that peer effects may not be a necessary condition for adoption.

[6] Those that reported at least one solar PV system already installed in their neighborhood when they were deciding to install.

Table 4
Marketing types and sources received by respondents. Each respondent could choose to rank up to five most influential marketing sources and types of marketing from among the following choices, including "Other".

Marketing types received by →	Marketing sources
• Email	• Local utility
• Referral	• Solar company
• Door-to-door	• Non-profit
• Online or social media	• Neighbor(s)
• Info session	• Friend(s)
• Radio/TV Ad	• Acquaintance(s)
• Print Ad	

4.2.4. Marketing received

Respondents were asked to specify the source and type of marketing they received in the order of influence on their decision (Table 4).

Table 5 presents the distribution of marketing types that were reported to be "most influential" in the decision process. Of the majority of respondents (76%) that responded to the "most influential form of marketing received" question, 43% (165) were exposed to more than one marketing type. Door-to-door marketing (77; 27%) was the most common most influential marketing source. However, other marketing types appear to be influential too, suggesting heterogeneity in what forms of marketing may be most effective.

Among the subset of respondents ($N = 106$) that supplied valid answers to questions on *both* the type of marketing and the source from which they received the most influential marketing, solar companies conducted the most influential marketing (78, 74%); they dominated every type except referral, which was dominated by friends. However, these referrals were likely also incentivized by solar companies. Thus, overall, solar companies appear to be using multiple marketing strategies and are also the most effective influence agents (through marketing).

Furthermore, for adopters who have PV systems already installed in their neighborhoods, door-to-door marketing has a significant relationship with the value of information they receive from their neighbors: such adopters report that information from neighbors is very important or extremely important *less* frequently than expected under independence. Adopters who are influenced by referrals also have a significant dependence with the value of information from their neighbors: they report that such information is very important or extremely import *more* frequently than expected under independence. These findings suggest that *the value adopters place on information from their neighbors is conditioned by the type of marketing they receive*. When installers make first-contact with an adopter, adopters attribute less value to interactions with neighbors, even though the presence of PV systems in the neighborhood may have initially provided direct or indirect motivation to consider installing solar. Conversely, when a neighbor adopts and then refers another neighbor to the installer (a process also likely to be funded by the installer), adopters value interactions with neighbors more.

4.3. Ending the decision-making period

4.3.1. Final decision to install

This section explores the relationship between the spark event

Table 5
Marketing types by influence. Horizontally, they are arranged by frequency of each marketing type as a responses to the question of most influence with the most frequent at the left.

Most influential	Door-to-door	Print Ad	Other	Radio/TV Ad	Online or social media	Email	Referral	Info session
n = 287	77	43	40	39	36	19	18	15

at the start of the decision-making process and the importance of factors that dominate its end. As shown in Table 6, respondents identified the importance of a set of factors in their final decision by answering a series of five-point Likert items ranging from “not important at all” to “extremely important; ” the list of factors, excluding the write-in option for “Other”.

The median response for all but two factors was “very important;” only foreign energy dependence and innovation were “moderately important.” However, adopters value these factors differently depending on their spark event. Those whose spark event was “thinking about retirement planning” report that a sound financial investment, less dependence on foreign energy, hedging against future electricity rate increases, and less dependence on the local utility were either “Very important” or “Extremely important” more frequently than expected under independence. The “recent increase in electricity rates” spark event is associated with more frequent responses that hedging against future rate increases and decreasing dependence on the local utility is very important or extremely important than expected. This suggests that increases in nominal electricity rates are playing on customers' psyches; in response to these increases some customers are looking for alternative options to hedge against future rate increases. SI-6 provides additional details on variations in motivating factors for those with or without existing systems in the neighborhood.

Interestingly, Fisher's exact test reveals no significant relationships between responses to the importance of the “main motivation to adopt” factors and the eventual method of acquisition chosen by respondents. Thus while spark events and the main motivation to adopt are correlated, as expected, the motivation to adopt does not appear to be determining the mode of adoption (buy, lease, or PPA). Next we discuss the factors that indeed impact the mode of adoption.

4.3.2. Determining method of acquisition

To determine which factors affect the method of acquisition, respondents specifically identified the degree to which a set of factors (“determinant” factors) determined their decision to buy, lease, or enter a PPA by answering a five-point Likert item for each factor in which they chose an option ranging from “Strongly disagree” to “Strongly agree.” The list of factors is shown in Table 7.

The majority (211, 56%) of respondents either agree or strongly agree that availability of upfront funds determine their method of acquisition. Other important determinants were calculated financial returns and operations and maintenance (O&M) concerns. These determinant factors shed light on the mechanisms at work during the decision-making process, as they have dependencies with both spark events and methods of acquisition.

First, we examine the spark events. Direct marketing – the most popular spark event (see Section 4.2.1) – is associated with more frequent agreement that solar contractor advice and credit rating determine their method of acquisition. This is further evidence that adopters tend to depend substantially upon solar contractors during the decision-making period. Respondents with solar systems already in their neighborhood report agreement that their acquisition-method decision was determined by conversation with their neighbors more frequently than expected under independence. These findings suggests that interactions with installer and neighbors have a role in determining not only if an adopter will install solar (see Section 4.2.3) but also in informing the method by which solar is installed.

Second, we explore the relationships between the “determinant” factors and the method of acquisition. There is a strong dependence between the importance of O&M concerns and the method of acquisition: when O&M is important, respondents choose TPO more frequently than expected under independence. Similar to participants in the automobile market, these adopters prefer offloading a portion of the risk associated with adopting an emerging technology to the company that actually owns the equipment [36]. Relatedly, those that buy report strong agreement less frequently and disagreement or strong disagreement more frequently (than expected under independence) that the method of acquisition decision was determined by the importance of O&M concerns. Furthermore, those that agree that the availability of upfront funds or contractor advice determined their method of acquisition also adopt TPO models more frequently than expected (see SI-7 for additional details on the impact of the availability of upfront funds on choice to take out a loan when purchasing outright).

This begs the question that if TPO is so attractive from O&M and upfront cost perspective – factors that have driven the recent rise in the adoption of the TPO model [18] – then why are some adopters still buying their systems outright? To address this question, the most relevant group of adopters includes those that had the option available to pursue TPO yet choose to buy – let's call this group the “Buying-Wins” group (N = 88). Fisher's exact test reveals a dependence between the Buying-Wins group and reporting that the method of acquisition was determined by the calculated financial returns (compared to those that had both an option to buy and to pursue TPO and chose TPO); the Buying-Wins group reports strong agreement that the method of acquisition was determined by the calculated financial returns more frequently than expected under independence. Furthermore, the Buying-Wins group calculates payback period, return on investment, and net present value significantly more frequently than expected under independence.

Within the Buying-Wins group, for the subgroup that also rate the importance of installing solar PV as a financial investment as very important or extremely important, there is a significant dependence between the decision to buy, lease, or enter a PPA and agreement that the decision is determined by the calculated financial returns. This subgroup reports strong agreement that calculated financial returns determine the decision more frequently than expected under independence. These findings describe a subset of adopters that are financially savvy and, in the absence of concerns about O&M, approach the decision to install solar PV largely as an investment vehicle and find buying as the right mode to do so. In other words, this group appears to be evaluating the cost-benefit of solar over a longer time horizon than the 15–20

Table 6
Main factors driving the final decision to adopt PV.

- Your evaluation that solar is a good financial investment
- Staying at the frontier of technological innovation
- Decreased dependence on foreign sources of energy
- Hedging against future increases in electricity prices
- Becoming less dependent on your local utility
- Reducing impact on the environment by using a renewable energy source

Table 7
Factors affecting the choice of the method of PV acquisition.

• Operation and maintenance concerns	• My solar contractor's advice
• Conversations with solar owners *outside* my neighborhood	• The complexity of the lease or PPA
• Conversations with solar owners in my neighborhood	• The length of the term associated with the lease or PPA
• The calculated financial returns	• My credit rating at the time
• Availability of funds to pay upfront	

typical in TPO contracts. Thus this group appears to be using a lower (implied) discount rate.

The relationship of O&M concerns and the importance of financial returns with the decision to pursue third-party ownership (given that the respondent had third-party ownership options available) is further explored in a logit model. The model takes the decision to acquire via third-party ownership *given* that the respondent had an option available (denoted by *ThirdParty*) as a dependent variable and includes a selection of spark events previously determined to be potentially relevant and controls as independent variables. The model takes the form:

$$logit(\Pr[ThirdParty]) = \overrightarrow{\beta}\overrightarrow{X}, \tag{1}$$

where $\overrightarrow{\beta}$ is a vector of coefficients estimated using maximum likelihood on $\overrightarrow{X}$, a vector of independent variables of interest and controls. Overall, when controlling for neighbor contact, decision period, decision-making factors, spark events, and relevant demographics, financial returns and concerns about O&M remain significant determinants of mode of adoption (see SI-8 for the full specifications of the model). That impact is mediated by the importance of financial returns: all else equal, respondents that value financial returns as very important or extremely important and have the option to lease or enter a PPA are about 25% *less* likely to pursue TPO. While consistent with the discussions earlier in this section, this finding is not robust to different model specifications (see Table A4 in SI-8). We note two additional significant influences on the method of PV acquisition (models 2a and 2b in SI-8): perception of higher complexity of the lease contract significantly increases the odds of buying, while lower income compared to the median respondent significantly increases the odds of TPO. Finally and most importantly, *ceteris paribus*, respondents that regard O&M concerns as very important or extremely important and have the option to lease or enter a PPA, have about 40–50% higher odds of pursuing TPO. This finding that higher O&M concerns significantly increases the odds of pursuing TPO is robust across different model specifications; in fact, the magnitude of this effect is even stronger depending on the model (see Table A4 in SI-8).

5. Conclusion

Using matched survey and solar program data for residential PV adopters in northern California, this paper focuses on two aspects of the PV adoption decision process: (i) the role of information channels, especially from neighbors and installers, in sparking interest among potential PV adopters and in providing them with valuable information through the decision process to help overcome barriers and uncertainties associated with PV adoption; and (ii) factors driving the choice of PV adopters between the different modes of PV adoption (buy versus third-party ownership).

We find that the key motivational and salient factors that drive households to consider solar in the first place are frequently installer-initiated – as in the case of the direct-marketing spark event, or related to planning for the future (say, impending retirement), or an increase in electricity rates. Peer effects – the influence of neighbors who already have PV systems – also provide a common motivator to consider installing solar. Furthermore, for about 13% of those exposed to peer effects the decision to adopt is a direct outcome of peer effects. Overall, peer effects are a key information channel in the spread of solar in the studied area. Thus *ex ante* consideration of peer effects in the design of policies and solar programs is important and offers opportunities to accelerate PV adoption [10,25]. It is an interesting and largely open question if, and to what extent, peer effects are also important in residential PV adoption in non-U.S. markets globally.

Installers also have an impact on adopters' information gathering process – more than 50% of respondents value information from solar installers as very or extremely important. When installers initiate the decision-making period they can dominate other streams of information, emerging as the primary source of information for their customers. Direct marketing in particular has a chilling effect on adopters' tendency to reach out to and to value information from neighbors and acquaintances, suggesting that it can serve as a substitute for information obtained from neighbors. A critical insight from the apparently competing information sources – peers and installers – is that the value placed on information sources is conditional on events that occur early in the decision-making process – such as marketing.

Consistent with broader trends in both California and the U.S. [3,37], respondents in our sample have a tendency to buy their PV systems outright, but are rapidly shifting towards TPO methods since 2012. We find some support that concern about the availability of upfront funds favors TPO, while a higher emphasis on the importance of financial returns favors buying. Concern about O&M appears to have by far the most consistent impact on the method of acquiring PV: higher O&M concerns favor TPO. We also identify two important subgroups among adopters: one group that appears to chose TPO in order to shift O&M risks to the TPO company, and another group that has the option to choose TPO but actually ends up buying outright as a financially more prudent pathway to adoption. A key implication of this finding is that different business models address important barriers associated with PV adoption differently and hence unlock different segments of potential adopters. Thus policies and programs should create conditions that enable different ownership models to operate in the market.

Finally, a further insight has emerged during the analysis: we find that the decision to adopt solar PV is not undertaken in a vacuum. An overwhelming majority (82%) co-adopts an energy-related product (energy efficiency, electric vehicle, etc.).[7] Thus solar adopters do other things at or about the same time as adopting solar that could also impact home value and electricity consumption. This finding signals complications for analyses attempting to estimate the *broader* financial benefits and costs of solar PV adoption, especially when assessing the impact of solar adoption on home value or electricity consumption changes. Such analyses must carefully control for confounding factors.

[7] The development of a larger home energy improvement plan may be a by-product of the California solar PV installation subsidy application process; an energy efficiency audit is the first step in applying for the rebate [39].

Acknowledgments

We thank Carolyn Davidson, Easan Drury, and Scott Robinson for valuable feedback and insights. This work was funded by the National Renewable Energy Laboratory (Subcontract # XGG-3-23326-01). VR acknowledges support from the Elspeth Rostow Memorial Fellowship. All remaining errors are ours alone.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2015.11.080.

References

[1] S. Pacala, R. Socolow, Stabilization wedges: solving the climate problem for the next 50 years with current technologies, Science 305 (2004) 968–972, http://dx.doi.org/10.1126/science.1100103.
[2] F. Iacobescu, V. Badescu, The potential of the local administration as driving force for the implementation of the National PV systems Strategy in Romania, Renew. Energy 38 (2012) 117–125, http://dx.doi.org/10.1016/j.renene.2011.07.014.
[3] GTM Research/SEIA: U.S. Solar Market Insight, U.S. Solar Market Insight Report: Q2 2014: Executive Summary, 2014. http://www.greentechmedia.com/research/ussmi.
[4] DSIRE, Database of State Incentives for Renewables & Efficiency, 2014. http://dsireusa.org.
[5] S. Carley, Distributed generation: an empirical analysis of primary motivators, Energy Policy 37 (2009) 1648–1659, http://dx.doi.org/10.1016/j.enpol.2009.01.003.
[6] Energy Star, Federal Tax Credits for Consumer Energy Efficiency, 2014, 2013. http://www.energystar.gov/index.cfm?c=tax_credits.tx_index.
[7] M. Fischlein, T.M. Smith, Revisiting renewable portfolio standard effectiveness: policy design and outcome specification matter, Policy Sci. 46 (2013) 277–310.
[8] G. Barbose, N. Darghouth, S. Weaver, R. Wiser, Tracking the Sun VI: an Historical Summary of the Installed Price of Photovoltaics in the United States from 1998 to 2012, Lawrence Berkeley National Laboratory, Berkeley, CA, 2013.
[9] W. Jager, Stimulating the diffusion of photovoltaic systems: A behavioural perspective, Energy Policy 34 (2006) 1935–1943.
[10] V. Rai, S.A. Robinson, Effective information channels for reducing costs of environmentally-friendly technologies: evidence from residential PV markets, Environ. Res. Lett. 8 (2013) 14044.
[11] G. Kumbaroğlu, R. Madlener, M. Demirel, A real options evaluation model for the diffusion prospects of new renewable power generation technologies, Energy Econ. 30 (2008) 1882–1908.
[12] C. Davidson, D. Steinberg, R. Margolis, Exploring the market for third-party-owned residential photovoltaic systems: insights from lease and power-purchase agreement contract structures and costs in California, Environ. Res. Lett. 10 (2015) 24006.
[13] E. Drury, M. Miller, C.M. Macal, D.J. Graziano, D. Heimiller, J. Ozik, et al., The transformation of southern California's residential photovoltaics market through third-party ownership, Energy Policy 42 (2012) 681–690.
[14] A. Faiers, C. Neame, Consumer attitudes towards domestic solar power systems, Energy Policy 34 (2006) 1797–1806.
[15] R. Margolis, J. Zuboy, Nontechnical Barriers to Solar Energy Use: Review of Recent Literature, National Renewable Energy Laboratory, U.S. Department of Energy, 2006.
[16] V. Rai, A.L. Beck, Public perceptions and information gaps in solar energy in Texas, Environ. Res. Lett. 10 (2015) 74011, http://dx.doi.org/10.1088/1748-9326/10/7/074011.
[17] V. Rai, K. McAndrews, Decision-making and behavior change in residential adopters of solar PV, in: Proc. World Renew. Energy Forum, Denver, Color, 2012.
[18] V. Rai, B. Sigrin, Diffusion of environmentally-friendly energy technologies: buy versus lease differences in residential PV markets, Environ. Res. Lett. 8 (2013) 14022.
[19] L.H. Shih, T.Y. Chou, Customer concerns about uncertainty and willingness to pay in leasing solar power systems, Int. J. Environ. Sci. Technol. 8 (2011) 523–532.
[20] P. Nelson, Information and consumer behavior, J. Polit. Econ. (1970) 311–329.
[21] C. Wilson, H. Dowlatabadi, Models of decision making and residential energy use, Annu. Rev. Environ. Resour. 32 (2007) 169–203.
[22] T. Dietz, Narrowing the US energy efficiency gap, Proc. Natl. Acad. Sci. 107 (2010) 16007–16008.
[23] R. Kemp, M. Volpi, The diffusion of clean technologies: a review with suggestions for future diffusion analysis, J. Clean. Prod. 16 (2008) S14–S21.
[24] P.C. Stern, What Psychology Knows About Energy Conservation, Am. Psychol. 47 (1992) 1224–1232.
[25] B. Bollinger, K. Gillingham, Peer effects in the diffusion of solar photovoltaic panels, Mark. Sci. 31 (2012) 900–912.
[26] P. DiMaggio, H. Louch, Socially embedded consumer transactions: for what kinds of purchases do people most often use networks? Am. Sociol. Rev. (1998) 619–637.
[27] E.M. Rogers, Diffusion of Innovations, Simon and Schuster, 2010.
[28] M. Graziano, K. Gillingham, Spatial patterns of solar photovoltaic system adoption: the influence of neighbors and the built environment, J. Econ. Geogr. (2014) lbu036.
[29] G. Blackburn, C. Magee, V. Rai, Solar Valuation and the Modern Utility's Expansion into Distributed Generation, Electr. J. 27 (2014) 18–32.
[30] N.R. Darghouth, G. Barbose, R. Wiser, The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California, Energy Policy 39 (2011) 5243–5253.
[31] K. Gillingham, H. Deng, R. Wiser, N. Darghouth, G. Barbose, G. Nemet, et al., Deconstructing Solar Photovoltaic Pricing: the Role of Market Structure, Technology, and Policy, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US), 2014.
[32] S.A. Robinson, V. Rai, Determinants of spatio-temporal patterns of energy technology adoption: an agent-based modeling approach, Appl. Energy 151C (2015) 273–284. http://dx.doi.org/10.1016/j.apenergy.2015.04.071 (accessed 10.07.15).
[33] V. Rai, S.A. Robinson, Agent-based modeling of energy technology adoption: empirical integration of social, behavioral, economic, and environmental factors, Environ. Model. Softw. 2015 (2015) 163–177, http://dx.doi.org/10.1016/j.envsoft.2015.04.014.
[34] H. Zhang, Y. Vorobeychik, J. Letchford, K. Lakkaraju, Data-Driven Agent-Based Modeling, with Application to Rooftop Solar Adoption, in: E. Bordini Weiss, Yolum (Eds.), Proc. 14th Int. Conf. Auton. Agents Multiagent Syst., Istanbul, Turkey, 2015.
[35] J.M. Nolan, P.W. Schultz, R.B. Cialdini, N.J. Goldstein, V. Griskevicius, Normative social influence is underdetected, Personal. Soc. Psychol. Bull. 34 (2008) 913–923.
[36] S. Dasgupta, S. Siddarth, J. Silva-Risso, To lease or to buy? A structural model of a consumer's vehicle and contract choice decisions, J. Mark. Res. 44 (2007) 490–502.
[37] California Solar Initiative, Working Data Set, 2014. http://www.californiasolarstatistics.ca.gov/current_data_files/.
[38] J.-P. Dubé, G.J. Hitsch, P. Jindal, The joint identification of utility and discount functions from stated choice data: An application to durable goods adoption, Quant. Mark. Econ. 12 (2014) 331–377.
[39] Go Solar California, Step 1: Energy Efficiency Audit, 2014, 2013. http://www.gosolarcalifornia.ca.gov/csi/step1.php.