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A Human-Centered Design Approach to Evaluating Factors in Residential Solar PV Adoption: A Survey of Homeowners in California and Massachusetts

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Abstract

The adoption rate of residential solar photovoltaic (PV) systems in the US has grown exponentially in the past two decades. However, from a human-centered design perspective, there is a lack of clear understanding of what current users need and want from solar PV systems and from the experience of installing solar. In this study, we interviewed 18 solar stakeholders and conducted surveys with 1773 homeowners including both solar adopters and non-adopters in California and Massachusetts. We analyzed the data using discrete choice theory and showed that cost savings, solar system reliability, installer warranty, and reviewers' rating of the installer were the most important factors when these homeowners considering purchasing a solar system. Preference differences were discovered between adopters and non-adopters, and based on state, age, and income. In addition, via surveying current solar adopters' experiences of installing residential solar panels, we found that solar owners ranked installer reliability to be even more important than price. The findings are intended to inform designers, engineers, and manufacturers in creating more compelling residential solar PV systems and to inform installers in designing better installation services. The ultimate goal is to promote this renewable energy technology and reduce global greenhouse gas emission.

Keywords

Residential Solar PV; Clean Energy Adoption; Human-Centered Design; User Needs and Preferences; Discrete Choice Modeling

1. Introduction

A solar photovoltaic (PV) system, often known as solar panels, converts sun power directly into electricity. It is a source of clean and renewable energy and thus can potentially play a key role in mitigating global greenhouse gas emissions. The residential sector is an important part of the solar market. Compared to utility level solar, residential solar has the benefit of being distributed, and thus reduces the load on power transmission [1]. Since they are mainly installed on rooftops of residences, they also reduce the solar land use [2].

The adoption rate of residential solar PV system in the US market has grown exponentially in the past two decades [3] thanks to drastically decreasing prices [4] and favorable government policies [5]. A wide variety of solar panels and inverters with a range of performance, functionality and reliability are currently available in the market, providing users with options and flexibility to customize their systems. In addition, a homeowner's interaction with solar installers is a crucial part of the experience of adopting solar [6,7]. In order to further market penetration of residential solar, it is vital to improve solar products [8, 9] and services [10] to bridge the gap between early adopters and the early majority [11].

This study takes a human-centered design approach, considers residential solar from the point of view of a consumer product and focuses on understanding homeowners' preferences for solar systems and solar installers. The ultimate goal is to provide guidelines for the design of solar systems and services that better meet user needs to further the diffusion of this clean energy technology. It poses the following research questions:

1. What attributes of solar PV systems and solar installers are the most important to homeowners?

It is well known that price, savings, payback periods, and monetary incentives are factors that homeowners consider when deciding to adopt residential solar PV systems. In this study, we aimed to identify non-economic attributes of solar PV systems and solar installers that homeowners would care about, and to evaluate what features were the most important to homeowners. We hope to identify and evaluate not only must-have or one-dimensional attributes, such as electricity production or solar panel energy efficiency; but also "delighter" attributes such as a panel's visual appeal [12].

2. How do preferences for solar PV systems and solar installers compare across homeowner demographics?

We expected homeowners in California and Massachusetts to have distinct preferences for solar PV systems because of the dissimilar solar irradiation levels and PV market maturity levels between the two states [7]. Similarly, we anticipated different preferences between solar adopters and non-adopters under the assumption that they would have different familiarity with solar PV systems, and different perceptions of the technology [13]. In addition, we expected age and income of the homeowners to influence their preferences. Previous studies have found that older households were less inclined to adopt micro-generation technologies [14] and adopters tend to have higher income and higher environmental awareness [15]. Identification of these preference heterogeneities among populations will help to guide the design of products and services for various market segments.

3. What are the gaps between homeowners' stated preferences for the experience of installing solar and their actual experience in installing solar?

We investigated the gap between the current experience that customers have in selecting and engaging with a solar installer, and their preferences for what they would ideally like to experience in order to pinpoint some of the potential barriers to solar adoption and potential directions to further improve solar products and services.

To address these research questions, field interviews with stakeholders were conducted to develop an initial understanding of consumer needs. Based on these interviews and literature review, a survey was designed and deployed to solar adopters and non-adopters in two US states, California and Massachusetts. Discrete choice experiments were used to investigate homeowners' preferences for features of solar PV system and solar installers. Section 2 introduces the background of this work and summarizes the existing discrete choice experiments for user preference studies of renewable energy products. Section 3 presents the research methods, including survey design and implementation, as well as data analysis. Section 4 reports and discusses the empirical results. Section 5 concludes the study.

2. Background

2.1. Key Attributes of Residential Solar PV Systems

Attributes of a solar PV system that influence market success have been investigated on three different levels: perceptual, design, and technical, from the general to the specific. Perceptual level attributes are concerned with how a product is regarded by consumers. Perceptions of the same product can easily vary across individuals and thus perceptual level attributes tend to be subjective. Technical level attributes are concerned with the technical specifications of a product. While technical attributes are frequently evaluated from technology development perspective, they may not be familiar to the product end-users. The design level, which bridges the previous two, considers attributes of a product that are both objective and tangible and can be easily understood by the end-users.

The most frequently considered perceptual level attributes of an innovative product are its *relative advantage*, *perceived risk*, *complexity*, *compatibility*, *trialability,* and *observability* [16,17]. Vasseur and

Kemp surveyed solar adopters and non-adopters in the Netherlands and found that the perceived affordability, environmental benefits, and ease of installation were key predictors for solar adoption [18]. Similarly, Zhai and Williams surveyed homeowners in Arizona, US, and found that compared to non-adopters, solar adopters perceived solar PV to be significantly more environmentally friendly, significantly less expensive, and require significantly less effort to maintain [13]. They also found that non-adopters considered cost to be a more important factor in their purchase decisions, while adopters considered environmental benefit and ease of maintenance to be more important. Claudy, Michelsen, and O'Driscoll compared Irish homeowners' perception of four microgeneration technologies, including micro wind turbines, wood pellet boilers, solar PV, and solar water heaters [19]. They found that solar PV was perceived to have the highest environmental benefit among the four. However, the perceived environmental benefit of solar PV had no significant influence on homeowners' willingness to pay. Instead, perceived independence from traditional sources of fuel was a strong predictor of homeowners' willingness to pay for solar PV.

Key technical attributes of a solar PV system include its efficiency [20,21], reliability [22] and durability [23,24], all of which are directly related to the system's energy production. Chen, Honda and Yang extracted technical specifications of solar panels from manufacturer data sheets and applied machine learning algorithms to actual solar PV market data in California, US to identify the key attributes that influence the product's market success [6]. The attributes explored included a solar panel's weight, size, power output, certifications, and cost, among others, and found that power warranty, efficiency at standard testing conditions, and time on the market were the three most critical attributes that influenced the product's market share. Frischknecht and Whitefoot assessed the revenue potential of four PV materials (monocrystalline silicon, polycrystalline silicon, tandem-junction amorphous silicon, and copper indium diselenide) by incorporating attributes such as temperature sensitivity, voltage, and current output, etc. of each type of solar PV into an engineering performance model [25]. They found that increasing power output of solar panels (by either increasing their voltage or current) could open new market of small roof-size population.

To investigate user preferences for solar PV systems, design level attributes that can be easily understood by end-users need to be identified. In Frischknecht and Whitefoot [25], attributes including system capacity, roof space, production warranty, payback time and net purchase price were presented to Australian homeowners in a survey to evaluate their preferences for solar PV systems. Scarpa and Willis studied British households' willingness to pay for micro-generation systems including solar PV, solar thermal and wind turbine, with considerations of the system capital cost, energy bill savings, maintenance cost, contract length, and inconvenience of installing systems [26]. Islam and Meade looked into

Canadian homeowners' preferences for solar PV regarding its initial investment, energy cost savings, CO_2 emission savings, payback period, and so on [27]. Bao, Honda, Ferik, Shaukat and Yang investigated US residents' preferences for solar panels' visual appearance while also considering their reliability, efficiency, unit price, and whether the system can be tied to the grid [28].

2.2. Discrete Choice Experiment

Discrete choice experiments have been widely used to study consumer preferences for renewable energy products. Bergmann, Hanley and Wright [29] and Ku and Yoo [30] studied the willingness-to-pay for the generic renewable energy in Scotland and Korea, respectively. Van Rijnsoever, Van Mossel and Broecks [31] and Borchers, Duke and Parsons [32] studied the public perception and acceptance of different energy technology, including PV solar, wind, biomass, coal, nuclear, and natural gas. Scarpa and Willis [26] studied the British households' willingness to pay for micro-generation systems such as PV solar, solar thermal and wind turbine. Kaenzig, Heinzle and Wüstenhagen [33] evaluated consumer preferences for electricity products with different proportion of renewable energy in Germany. Islam and Meade [27] investigated the impact of attribute preferences for residential solar PV systems on the adoption timing. Ladenburg and Dubgaard [34] and Bao, Honda, Ferik, Shaukat and Yang [28] investigated the visual appearance of offshore wind farms and solar panels, respectively, and their impact on people's willingness-to-pay and preferences.

The following two characteristics of these previous discrete choice experiments were observed. First, a majority of these studies treat renewable energy as a mere substitute for a traditional source of electricity with added environmental benefits [29–31]. Some studies also view renewable energy as part of the energy mixed provided by utility companies [32,33]. Consequently, these choice experiments focused on investigating the general public's acceptance of renewable energy and evaluated perceptual level attributes such as the impact on landscape and wildlife, reduction on air pollution, energy safety and supply security. Second, there was a strong emphasis on economic factors such as capital cost, maintenance cost, energy bill, payback period, and tax incentives for renewable energy. Some studies even included multiple of these economic factors into one single choice experiment [26,27]. Only a few choice experiment studies treated renewable energy as technology products and included design level attributes [26–28].

2.3. Research Gaps

Residential solar PV is a technology product in that it produces electricity using solar power and satisfies user needs for energy independence, lower energy bills, less environmental impact, and making a statement about their environmental beliefs [35]. While many existing studies investigated the perceptual level and technical level attributes of a solar PV system, few have looked at the design perspective or investigated the impact of solar PV system design on the diffusion of the technology.

In addition, the majority of US solar panels are installed by professional installers rather than by homeowners themselves, making solar installation and maintenance services provided by installers crucial to the user experience of adopting solar. This became especially true when third-party PV ownership [36] became popular. Solutions to simplify the solar installation process, such as plug-and-play PV systems [37,38], have emerged. Factors that can influence users' adoption experience such as information channels [39] and buy-versus-lease options [40] have been explored. However, studies in this area are still sparse.

To bridge these gaps, this study focuses on understanding user needs and preferences for the design of residential solar PV systems and the services provided by solar installers. Discrete choice experiments were designed and deployed with an emphasis on non-economic design attributes of solar systems and installation services. The overarching goal was to identify opportunities for improving the design of solar PV systems and solar installation services with the aim of accelerating the technology diffusion.

3. Method

3.1. Interviews with Solar Stakeholders

As the first step in understanding user needs for residential solar PV systems, semi-structured interviews were conducted with solar stakeholders. We interviewed eighteen residential solar PV system stakeholders in the New England region (17 in Massachusetts and one in Connecticut), including seven solar adopters, two homeowners who had considered but hadn't installed solar, one project manager from a Massachusetts public agency to advance clean energy, one municipal representative, one sales manager of a solar installation company, two energy consultants, and four solar "coaches" who voluntarily organized community based solar marketing. A snowball sampling method was used for recruiting interviewees.

Questions were asked to understand homeowners' decision-making process for adopting solar and the general process of solar installation. More specifically, homeowners were asked the important factors they considered or would consider when selecting solar installers and solar systems. Solar adopters were asked about their own experiences owning a solar system. Solar industry professionals were asked about the products and services they provided to solar adopters, the factors that they thought were most important to homeowners when installing solar, and policy incentives for promoting solar.

A list of attributes that could influence homeowners decision making on solar adoption were summarized from the interviews. The identified attributes of a solar system include price, payback period, appearance, efficiency, type of inverter, location of manufacturer, reliability, warranty, and environmental benefits of a solar system; the identified attributes of a solar installer include customer review, financing options, choice of equipment, responsiveness to communication, flexibility of system design, labor warranty, length of project, and financial stability.

3.2. Survey Design

After conducting interviews, a survey was designed to evaluate homeowners' preferences for residential solar PV systems and installation services on a large scale. A thorough process was taken to design the survey, especially the discrete choice experiments [41]. Multiple rounds of pilot studies were conducted, first with five homeowners to shape the questions and the wording, then with 36 respondents recruited on Amazon Mechanical Turk, a human intelligent crowdsourcing platform, for reading level and timing, and in the end with 120 respondents recruited via Peanut Labs, an online market research company, to test the data analytic methods. Modifications to the survey were applied based on the feedback of each round of pilot testing.

3.2.1. Discrete choice experiment attributes and levels

The survey included two discrete choice experiments, one for solar installers and the other for solar systems, assuming adopters would first choose an installer to work with and then choose a solar system to install among options that the installer would provide. Only a subset of the attributes identified in the interviews was included in the discrete choice experiments. The number of attributes was limited to six per choice experiment to keep the survey manageable for respondents. The importance of these factors to the solar adoption decision-making and the respondents' familiarity with these attributes were taken into consideration in the selection process. Price was not included as attribute because the price of installing a solar system depends on the system size, which can vary drastically according to a household's energy demands. Instead, percentage savings in electricity over 25 years was used to represent the financial factors of installing solar.

The attributes and levels are summarized in Table 1. These levels of the attributes were selected to represent the current solar markets and the potential markets in the near future. Detailed introductions to the choice experiment attributes and levels were provided to the respondents in ways that homeowners who had little knowledge about residential solar PV systems could easily understand. Illustrations were provided to help explain some of the attributes. These were to make sure all respondents, regardless of their previous experience with residential solar PV systems, would have the same basic understanding of the attributes to make informed responses to the discrete choice questions. Introductions to the attributes as appeared in the survey are presented in APPENDIX I.

Each discrete choice question presented three options of solar installers or systems with random combinations of attribute levels. In addition, a "None" option was provided in each question, allowing the respondents to choose none of the three options. Prohibition rules were set to avoid dominant bundles of attributes (e.g. the best functionalities and the highest savings were prohibited to appear together in any solar system options). Each discrete choice experiment included sixteen questions. Sawtooth Software was used to design the questionnaires.

Table 1 Attributes and Levels of the discrete choice experiments

Discrete Choice Experiment of the Installers	
Attributes	**Levels**
Independent Reviewer Rating	Average (3 stars), Good (4 stars), Excellent (5 stars)
Installer-Customer Collaboration Style	Independent, Moderately Collaborative, Collaborative
Equipment Technology	Cutting-Edge, Standard, Traditional
Total Project Time	1/2 Month, 1 Month, 2 Months, 4 Months
Warranty	5 Years, 15 Years, 25 Years
Savings In 25 Years	10%, 25%, 40%, 55%, 70%
Discrete Choice Experiment of the System	
Attributes	**Levels**
Panel Efficiency	15.5%, 18.0%, 20.5%, 23.0%, 25.5%
Panel Visibility On Roof	High, Low
Inverter Type	Central Inverter, Micro-Inverter, Power Optimizer
Failures In First Five Years	0 Failures, 1 Failure, 2 Failures, 5 Failures
Environmental Benefits (reduced CO_2 emission equivalent)	3 Acres of Forest, 6 Acres of Forest, 9 Acres of Forest
Savings In 25 Years	10%, 25%, 40%, 55%, 70%

At the beginning of the discrete choice experiments, the respondents were asked to imagine shopping for solar systems. For those who had already installed solar panels, they were asked to imagine this was their first time shopping for solar. The scenario asked the respondents to imagine that they had just bought and renovated a house, and decided to invest some extra budget into solar panels to save money on electricity in the long run. The intention of the scenario was to encourage respondents to express preferences as if they were making decisions in the real world. In addition, the scenario exempted the respondents from concerns such as old roofs or limited budget to discourage them from always choosing "None" even if they could not adopt solar in the real world for these reasons.

3.2.2. Questions about the solar installation process and respondent demographics

Solar adopters were asked about their solar systems, including the year of solar installation, method of financing, cost of installing solar, and length of installer warranty. In addition, solar adopters were asked about the process of installing solar, including the number of installers explored before signing a contract (“exploring" a solar installation company included talking to their sales representative, visiting their website/store/office, receiving their proposal, and so forth), the number of installers who visited their home, the number of panel choices provided by the installers they chose to work with (panels of different brands, models or efficiencies were considered different choices), the solar adopters’ level of involvement when designing the systems (including selecting the models of panels and inverters, deciding the system capacities, etc.), and the time spent on different phases of installation. The solar adopters also reported their electricity bills before and after installing solar and evaluated the performance of their solar systems.

All participants were asked demographic information including the state they reside in, their gender and age, along with their household yearly income at the time they installed solar.

3.3. Data Collection and Quality Control

The survey was active between late April to early October 2017 and was distributed via three channels: Peanut Labs, an online market research company, was used to collect responses from homeowners in California and Massachusetts; Qualtrics, another online market research company, was used to collect responses from solar adopters in the two states; and finally, connections to local solar adopter communities and solar installers were used to collect responses from more solar adopters. Screening questions at the beginning of the survey allowed only homeowners residing in California or Massachusetts to proceed. Additional screening questions were ask to decide if a homeowner had adopted solar or not.

Much effort was spent to ensure the quality of collected data. Prompts in the survey reminded respondents to read the materials and questions carefully. Time limits prevented respondents from clicking through the introduction pages too quickly. Control questions were used to screen the responses. Responses that passed the control questions, provided meaningful responses, provided consistent demographic information, and spent enough time on the survey were kept for further analysis [42,43]:

3.4. Data Analysis

3.4.1. Choice modeling

Two models were used to analyze the results of the discrete choice experiments: the Hierarchical Bayes (HB) model and the logit model [44].

An HB model uses Bayesian procedures to estimate parameters of a mixed logit model, which describes the choice probability as:

$$P_{ni} = \int \frac{\exp(\beta x_{ni})}{\sum_j \exp(\beta x_{nj})} f(\beta) d\beta \quad (1)$$

where P_{ni} is the probability of person n choosing option i from a pool of options js; x_{ni} is the vector of the attribute levels of option i that person n has; and β is the vector of the corresponding coefficients. The elements of vector β are random variables following distribution $f(\beta)$, representing the preference heterogeneity among the population. In this study, HB models were used to capture the overall preferences of the survey respondents. We assume β follows normal distributions.

A standard logit model is a special case of a mixed logit model, where the coefficient β is degenerate at fixed parameter b. In consequence, its choice probability becomes:

$$P_{ni} = \frac{\exp(b x_{ni})}{\sum_j \exp(b x_{nj})} \quad (2)$$

In this study, logit models were used when investigating the interaction effect between respondents' demographics and their choice patterns. Including interaction effects increased the number of explanatory variables of the models. To prevent overfitting, logit models were used instead of HB models for simplicity.

The importance of an attribute was calculated as the relative range in that attribute's utility values [45]. The importance values of all attributes of a model should add up to one. For the HB models, the attribute importance was first calculated on individual levels and then summarized as the mean and standard deviation over all respondents.

3.4.2. Analysis of solar installation questions and demographic questions

Statistical summaries of the responses to the solar installation questions and demographics questions were reported. The distributions of the responses were presented in the format of mean ± standard deviation if the variables were continuous, and were presented as contingency tables or bar plots if the variables were categorical. T-test, chi-squared test, or analysis of variance (ANOVA) were conducted to compare the responses between different groups, for example between residents of different states or between solar adopters and non-adopters. When conducting chi-squared testing, categories with too few observations were combined to avoid violations of the chi-squared approximation.

4. Results and Discussion

In total, 2633 complete responses were received and 1773 responses passed all quality control rules, 1053 from California and 720 from Massachusetts; 303 California respondents and 260 Massachusetts respondents were solar adopters.

The number of responses from solar PV adopters and non-adopters from each state and distributions of their gender, age, and yearly household income are summarized in Table 2. Since we intentionally invited solar adopters to take the survey, the proportions of the adopters to non-adopters do not reflect those among the general US population.

Table 2 Demographic distributions of the survey respondents

	California		**Massachusetts**	
	Adopters	**Non-Adopters**	**Adopters**	**Non-Adopters**
Total	303	750	260	460
Gender				
Female	132 (43.6%)	461 (61.5%)	92 (35.4%)	302 (65.7%)
Male	171 (56.4%)	288 (38.4%)	163 (62.7%)	155 (33.7%)
Self-defined	0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (0.7%)
Prefer not to answer	0 (0.0%)	1 (0.1%)	5 (1.9%)	0 (0.0%)
Age				
18-24	11 (3.6%)	53 (7.1%)	9 (3.5%)	28 (6.1%)
25-34	33 (10.9%)	114 (15.2%)	21 (8.1%)	80 (17.4%)
35-44	43 (14.2%)	157 (20.9%)	60 (23.1%)	102 (22.2%)
45-54	52 (17.2%)	175 (23.3%)	65 (25.0%)	99 (21.5%)
55-64	72 (23.8%)	143 (19.1%)	48 (18.5%)	91 (19.8%)
>= 65	90 (29.7%)	101 (13.5%)	51 (19.6%)	59 (12.8%)
Prefer not to answer	2 (0.7%)	7 (0.9%)	6 (2.3%)	1 (0.2%)
Household Income (at the time when adopting solar, if solar adopter)				
<= $24,999	3 (1.0%)	39 (5.2%)	3 (1.2%)	17 (3.7%)
$25,000-49,999	25 (8.3%)	132 (17.6%)	9 (3.5%)	77 (16.7%)
$50,000-99,999	82 (27.1%)	298 (39.7%)	39 (15.0%)	176 (38.3%)
$100,000-199,999	124 (40.9%)	200 (26.7%)	110 (42.3%)	143 (31.1%)
>=$20,000	44 (14.5%)	45 (6.0%)	68 (26.2%)	19 (4.1%)
Prefer not to answer	25 (8.3%)	36 (4.8%)	31 (11.9%)	28 (6.1%)

4.1. Discrete Choice Analysis with HB Models

The part-worth utilities of each attribute level was estimated with a HB model. Effect coding was used so that the summation of the level part-worths of an attribute would equal to zero. When estimating each model, 100,000 iterations were performed and the first 50,000 iterations were considered burn-in (allowing the simulation to reach its equilibrium) [44]. After convergence, every tenth draw was retained, resulting in 5,000 iterations for calculating the part-worths. The results are visualized in Figure 1 and are recorded in APPENDIX II. The overall trends of the part-worths were consistent with our expectations.

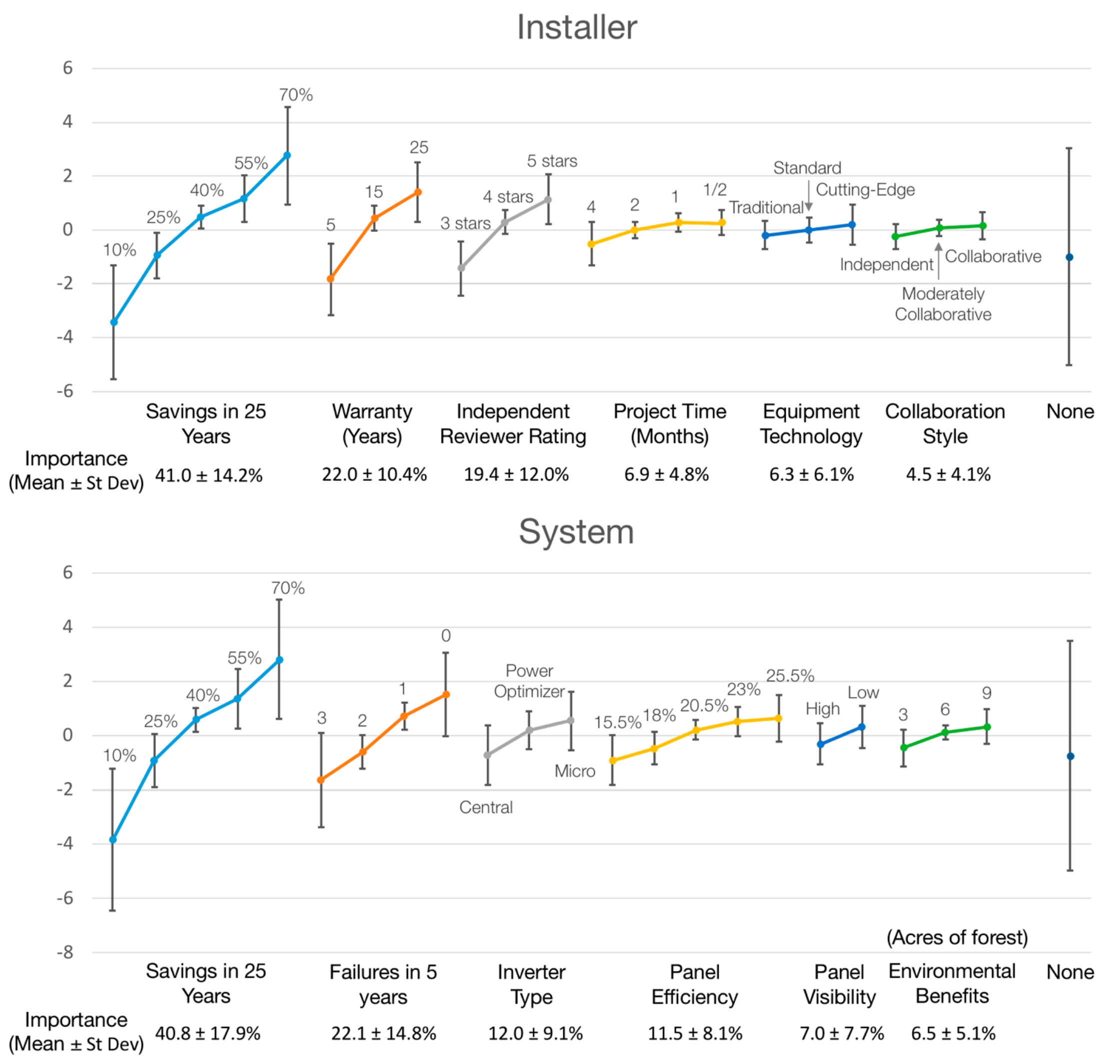

Figure 1 Estimated part-worths and attribute importance of the solar installer discrete choice experiment (top) and solar system discrete choice experiment (bottom) using HB models.

Note: Error bars represent the part-worth standard deviations. The attributes are presented in order from the most important (left) to the least important (right).

The mean part-worths of the "None" options were negative in both the installer and system choice models, indicating overall the respondents were more likely to choose an installer or system option instead of the None option. The part-worth standard deviations were large, indicating large variation among the respondents.

For solar installers, higher independent reviewer rating, longer warranty, and higher savings had higher mean part-worths. Among the three collaboration styles, Independent was on average the least preferred and Collaborative was on average the most preferred. However, the standard deviations of their part-worths were larger than the means, indicating a large preference variation as a significant number of respondents still preferred an independent style over a collaborative one. This result was also reflected in the interviews with the solar adopters, that some solar adopters had strong opinions on system design and would prefer their systems to be custom made, while others prefer installers to make all installation decisions for them. For panel technologies, the cutting-edge had the highest and the traditional had the lowest mean part-worths, indicating the more advanced technology was, in general, more preferred. Again, there was large variation among the respondents. Since cutting-edge technology was on the market for less time compared to standard and traditional technology, it was likely that some respondents would prefer the traditional technology to avoid potential risk. Overall, the longer the project time was, the lower its mean part-worth would be. The difference between the part-worths of 1/2 month and 1 month was small, suggesting that a 1-month project time was short enough for homeowners in general, and further shortening the project time does not provide extra benefits.

For solar systems, the higher the efficiency, the less frequent the failures, the larger the environmental benefit, and again the higher the savings, the higher the mean part-worths. In addition, the respondents generally preferred micro-inverters over power optimizers and preferred both of them over central inverters. On average, the respondents preferred low panel visibility better than high panel visibility, which was consistent with previous findings that solar panels which visually blend into the roof were considered more aesthetically pleasing [28]. Again, the part-worths' standard deviations were large, indicating there existed a significant proportion of respondents who preferred high panel visibility over low panel visibility.

Figure 1 also presents the attribute importance. Savings were by far the most important attributes of both installers and solar PV systems. This was not surprising considering that a major motivation for homeowners to adopt solar was to save electricity bills [46].

Warranty and the number of failures in five years were respectively the second most important attributes of the installer and system discrete choice. In contrast, the overall equipment technology, the panel efficiency, and the inverter type had lower importance values. These unexpected results suggest that homeowners care more about the system reliability and ease of maintenance than technology advancement per se. The low importance of panel efficiency was surprising and contradictory to a previous study which found that efficiency was the second most important factor in panel selection decisions [6]. One potential explanation was that the exact value of panel efficiency was a technical term that was hard to perceive by an average homeowner. The benefit of high panel efficiency could be perceived as higher energy production and consequently more energy bill savings, as does the benefit of micro-inverters and power optimizers. Therefore, unless a customer was technology savvy, they might not care much about the exact technical details of a solar system, but instead focus on the overall savings provided by the system.

Independent reviewer rating was found to be important in the installer discrete choice experiment. This was consistent with findings of previous studies that the recommendation from professionals was important to the consumers' adoption decision of micro-generations [14] and energy products [47]. Interestingly, the environmental benefit had a low importance value, even though being environmentally sustainable was another important motivation for homeowners to adopt solar [15,48].

4.2. Interactions Between Respondent Demographics and Attribute Preferences

To detect potential influence of respondents' demographics on their preferences for the solar installers and systems, interaction terms between the demographics and the solar attributes were estimated using logit models. Demographic variables including the state, solar ownership, yearly household income, and age were considered. All these four demographic attributes were found to link with homeowners' preferences for solar installers and systems. Results of the logit models are summarized in APPENDIX III. A selection of most significant interaction effects (p-value < 0.001) are visualized in Figure 2 and Figure 3 and are discussed below.

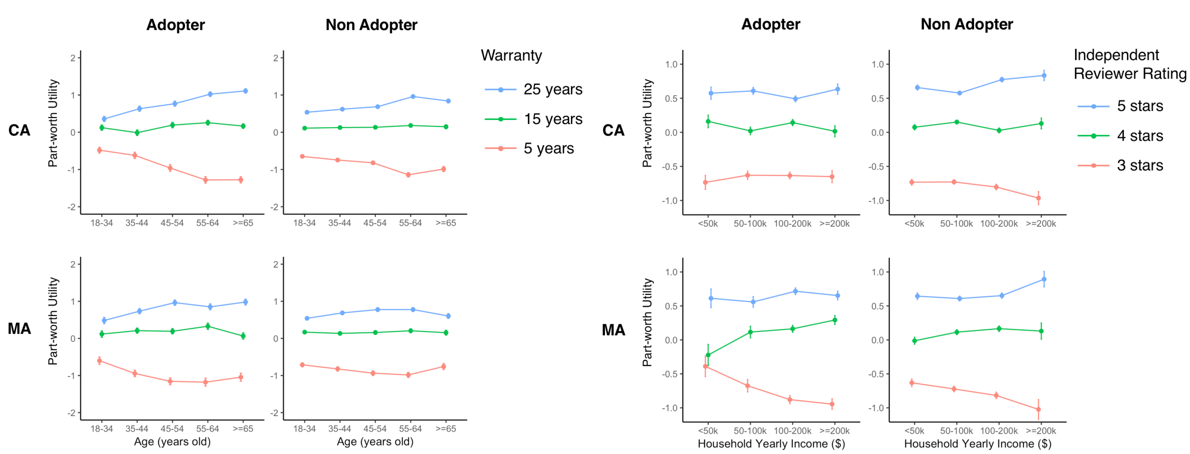

Figure 2 Interactions between age and warranty (left), and income and independent reviewer rating (right)

Note: Each point is a part-worth of attribute levels, estimated within each age or income group. Stratification and estimations were conducted within the adopter and non-adopter groups of each state to control for potential confounding effects between these demographic variables.

As shown in Figure 2, Homeowners' ages had significant and positive interaction with installer warranty, indicating older homeowners preferred longer warranties over shorter warranties more strongly compared to younger homeowners did. Independent reviewer rating had significant positive interaction with homeowners' household income, suggesting higher income homeowners tended to prefer higher rated installers more strongly compared to lower-income homeowners did.

In the system choice experiment, high panel visibility negatively interacted with age and income (Figure 3). Regardless of the state that homeowners resided in and their solar ownership, older and higher income homeowners consistently had much stronger preferences for low panel visibility over high panel visibility. However, among younger and lower income homeowners, the differences between preferences for the low and high panel visibility were smaller. In the <$50K income groups among adopters in both states, the average utilities of the high panel visibility were even higher than those of the low panel visibility. One potential explanation is that older and higher income homeowners tended to be concerned more about the aesthetics of their homes and thus preferred less visible panels, while younger and lower income homeowners preferred more visible panels as a statement about their environmental beliefs [35]. Another interpretation of this result might stem from the fact that solar panels are a technology that have grown significantly in adoption in the past 10 years [49] and in that time younger homeowners have grown accustomed to the appearance of panels on a roof in a way that older homeowners who grew up in an earlier era aren't. After controlling the effect of age and income, solar adopters on average did not prefer low visibility panels over high visibility panels as strongly as non-adopters did.

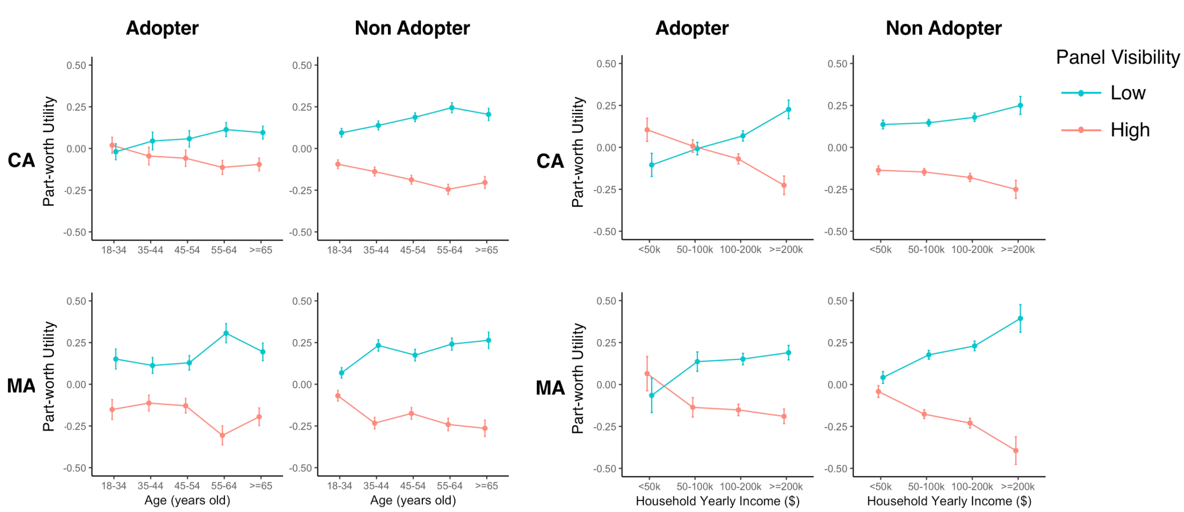

Figure 3 Interactions between age and panel visibility (left), and income and panel visibility (right)

Note: Each point is a part-worth of attribute levels, estimated within each age or income group. Again, stratification and estimations were conducted within the adopter and non-adopter groups of each state.

In addition, California homeowners on average cared less about if an installer work collaboratively or independently, and they cared less about the type of inverters, compared to Massachusetts homeowners. Higher income homeowners had stronger preference for the “delight features” of solar, such as cutting-edge equipment technology or low panel visibility. These results show the necessity of diversifying solar product and service features in order to appeal to different market segments.

Current solar adopters, who are presumably early adopters of the technology, tended to be different from the current non-adopters, some of whom might adopt solar in the near future. On one hand, it is important for solar installers and manufacturers to keep improving their products and services in order to respond to the changing market. On the other hand, education might be necessary for non-adopters to overcome any perceptual barriers to the adoption of solar PV.

4.3. Solar Adopters’ Experience in Installing Solar PV Systems

This section presents a selected summary of surveyed solar adopters’ experiences installing solar PV systems. More survey results are summarized in APPENDIX IV.

Solar Installer Selection. On average, California and Massachusetts solar adopters explored 2.42 ± 1.41 and 2.59 ± 1.70 installers respectively before signing a contract ($t=-1.300$, p-value = 0.194); and had 1.32 ± 1.26 and 1.75 ± 1.28 solar installers visit their residences respectively ($t = -3.936$, p-value <0.001***).

The survey showed ten reasons for choosing an installer. Respondents were asked to rate the importance of each on a 0-5 scale, where 0 was not applicable, 1 was slightly important, and 5 was extremely important. The average importance ratings were used to rank the 10 reasons. The results are summarized in Table 3. The rankings are similar between solar adopters in California and Massachusetts.

The top three criteria that the current solar adopters considered when selecting their installers were reliability, responsiveness and reasonable price. Reliability was rated to be the top concern, even more important than price. This result was reasonable considering that price only influenced the one-time payment, while an installer’s reliability was potentially key to the long-term savings. In addition, whether the installers were responsive or not appeared to be an important factor that influencing solar adopters’ decision-making, even though the installer-customer collaborative styles appeared to be the least important when homeowners making choices in the discrete choice experiments.

Consistent with the discrete choice experiment results, the models of PV panel and inverter were not important considerations of solar adopters in their decision-making process. Instead, the overall system configuration appeared to be more important. The importance ranking of “offered better labor warranty” was not very high. Considering the number one reason was “it was a strong company I could rely on in the future" we conjectured that the solar adopters were looking for installers who not only offered long warranties but would also stay in business for long enough to provide warranty service in the future.

"Better customer reviews" appeared to be important, consistent with the discrete choice experiment results. Also, this reason had much higher ranking compared to "recommended by friends/relatives". One possible reason could be because only a small percentage of homeowners had installed solar, thus the peer effect was weak and homeowners had to rely on external sources such as customer reviews to judge installer quality.

Table 3 Importance ranking of factors that solar adopters considered when selecting solar installers

Reason of selecting installer	Importance Ranking CA	MA
I believed it was a strong company I could rely on in the future	1	1
They were more responsive to my requests/questions	3	2
They offered a more reasonable price	2	3
They had better customer reviews	6	4
They offered a better overall system configuration	5	5
They offered a better labor warranty	4	6
They offered model(s) of PV panels that I liked better	7	8
They were recommended to me by friends/relatives etc.	9	7
They offered model(s) of inverters that I liked better	8	9
They offered a financing option that I wanted	10	10

Solar Installation Process. Choosing to purchase or lease the system appeared to make a difference in how much and when homeowners pay for their solar system, and also change homeowners' experience of installing solar (the distributions of types of financing solar adopters used are summarized in APPENDIX IV). Solar adopters who purchased their system had more choices of solar panels and were more involved in the system design and installation process. In addition, leasing the system appeared to link to an expedited solar installation process. This is a concrete example of differencing solar installation services to address the needs of different customers [40].

Figure 4 shows the distributions of number of panel choices offered by the installers and the solar adopters' self-reported level of involvement in the process of designing their systems. In general, solar adopters who purchased systems were offered more choices of solar panels, indicating they had more autonomy in making decisions in designing the system. This trend was significant in both states (California: chi-squared = 19.2, df = 3, p-value <0.001***; Massachusetts: chi-squared = 23.786, df = 2, p-value <0.001***). In addition, Massachusetts solar adopters who purchased their systems appeared to have more panel choices compared to California solar adopters who purchased (chi-squared = 12.092, df

= 3, p-value = 0.007**). However, there was no significant difference between solar adopters who leased their systems in the two states (chi-squared = 0.18789, df = 2, p-value = 0.910).

Solar adopters who purchased their systems also reported being more involved in the process of designing the system. The trend was consistent in the two states (California: chi-squared = 27.699, df = 4, p-value <0.001***; Massachusetts: chi-squared = 6.001, df = 2, p-value = 0.0498*). No significant differences were found between states.

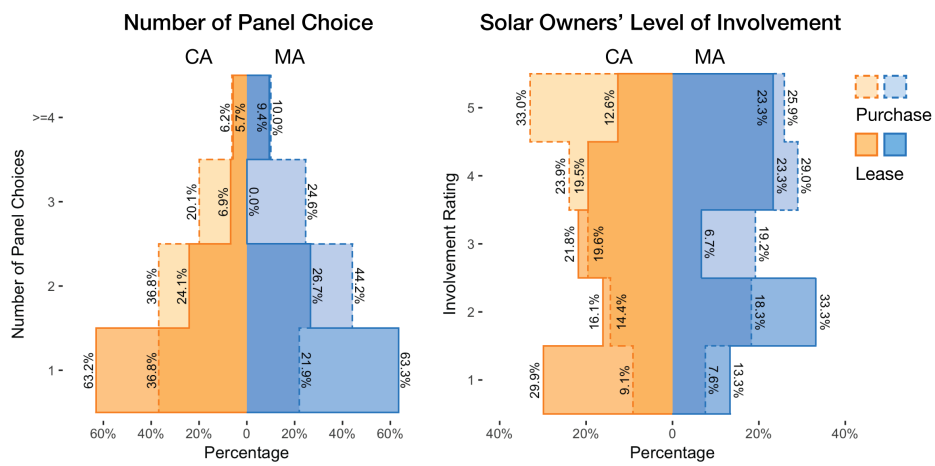

Figure 4 Number of panel choices offered to solar adopters by their installers (left); Solar adopters' self-reported level of involvement in the process of designing their systems (right, 1 – extremely uninvolved, 5 – extremely involved).

System Performance – For California adopters, a system failed an average of 0.115 ± 0.419 times annually, equivalent to 0.575 failures every five years. For Massachusetts adopters, the average system failure rate was 0.196 ± 0.546 times per year, equivalent to 0.980 failure every five years. The difference between the two states was marginally statistically significant (t = -1.95, p-value = 0.052). However, it should be noted that a substantial number of solar adopters took the survey within two years of installing their solar systems. Thus, these estimated failure rates could be biased towards the low end.

Figure 5 shows solar adopters' average electricity bill before and after installing solar in summer and winter respectively. The electricity bills were significantly reduced after installing solar in either summer or winter in both states (Summer California: chi-squared = 216.73, df = 6, p-value < 0.001***; Summer Massachusetts: chi-squared = 248.2, df = 6, p-value < 0.001***; Winter California: chi-squared = 203.59, df = 6, < 0.001***; Winter Massachusetts: chi-squared = 187.36, df = 6, p-value < 0.001***).

Figure 5 also presents self-reported electricity output of the solar systems. Less than 10% of solar adopters thought their systems were producing less electricity than expected. More than 90% of solar adopters thought their systems were producing at least as much as expected, if not more. There was no significant difference between the two states (chi-squared = 5.6635, df = 4, p-value = 0.2257).

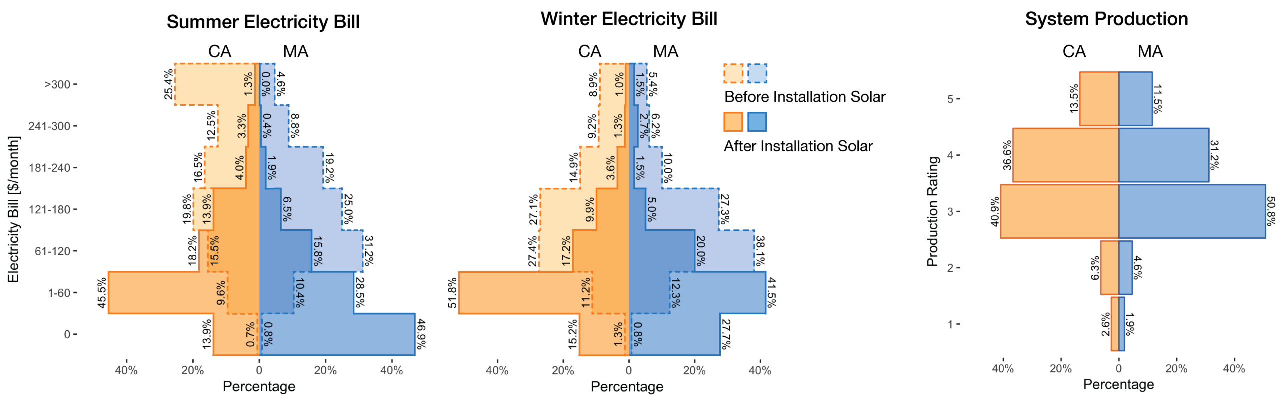

Figure 5 Average monthly electricity bills before and after installing solar in summer (left) and winter (middle); self-reported system production (right, 1 – much less than expected, 5 – much more than expected)

To summarize, the overall failure rates of the surveyed solar systems were lower than once every five years. In addition, the majority of the current solar adopters were satisfied with their system production. These are reassuring results and could be used to encourage future solar adoptions.

5. Conclusion

In this study, in-depth interviews were conducted with solar stakeholders, via which key design attributes of solar PV systems and installation were identified. A survey was designed based on these interview results and was deployed to 1,053 homeowners in California (a more mature market) and 720 homeowners in Massachusetts (a less mature market), including both solar adopters and non-adopters. Insights into user needs and preferences for residential solar PV systems and solar installation services were gained. The main contributions of this study are as follow:

Firstly, this study applied discrete choice experiments to study renewable energy systems and installation from a product and service design perspective. While previous literature focused on perceptual or technical aspects of residential solar, our study investigated solar attributes on a design-level that homeowners would be familiar with and refer to in their decision making on adopting solar. These attributes were identified via stakeholder interviews and were introduced to survey participants in language that homeowners with little experience with solar PV systems would understand, which helped to reveal realistic preferences.

Secondly, our survey data were collected from thousands of homeowners in two US states with varied age and household income, and the respondents covered both solar adopters and non-adopters. While previous studies often surveyed a single geographic region and surveyed only solar adopters or non-adopter, our broad survey coverage enabled comparison between different demographic groups and provided more comprehensive understanding of US homeowners' needs and preferences for solar PV.

The findings of the studies are useful to manufacturers to guide the design of their products and are valuable to installers to inform the design of their services. Additionally, these results can help calibrate simulation models for predicting future solar adoption and analyzing impact of policies on the solar market, which will provide insights to policy makers regarding how to effectively further the diffusion of solar PV technology to reduce global greenhouse gas emissions.

There are several opportunities for future investigation. While this current study was built on the assumption that different attributes of solar systems and installation are independent of each other, future work could incorporate engineering models to provide more realistic bundles of attributes. It would also be interesting to combine stated preference models from surveys with revealed preference models from market data to gain insights into homeowners' decision making.

Acknowledgement

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APPENDIX

APPENDIX I Discrete Choice Experiment Attribute Introduction

(Note: the following introductions are the original ones as presented in the survey)

Next, you will imagine shopping for solar panels. If you have installed solar already, please bear with us and pretend this is your first time shopping for solar.

Imagine that you have just bought and renovated a house. You have budgeted extra money for upgrades. Friends have told you that solar panels are a good investment because you will save money on electricity in the long run. Your roof is new and has the correct orientation for solar panels. All other conditions are also perfect for solar. You are now seriously considering installing solar panels, and are exploring available options.

You learn that solar panels are usually sold by solar installers. You need to first choose the installer to work with, and then select the solar system to install. In the next section, you will first read seven pages of information that will help you to make educated decisions when choosing an installer. **Please spend enough time on each page and read them carefully (the survey will not allow you to proceed if you spend too little time reading)**. After that, you will be given some questions to answer.

Solar Installers

A solar installer is a company that supplies and installs solar panels for homeowners. The major responsibilities of a solar installer include:

- Designing the solar system layout
- Selecting and installing the equipment
- Applying for construction and electricity permits
- Applying for rebates
- Maintaining the system

You discover a website for comparing the solar installers in your area. Below is an example profile of a solar installer on the website. Go to the next page to learn the details of each feature.

	Example Installer
Independent Review Rating	Good ★★★★☆
Installer-Customer Interaction	Collaborative
Equipment Technology	Standard technology
Total Project Time	2-month project time
Warranty	15-year warranty
Savings in 25 Years	40% savings

Independent Reviewer Rating

Imagine that an independent product testing organization (like Consumer Reports) has evaluated solar installers based on customer reviews and other factors, such as financial stability, years in the market and so forth. The website shows you installers with at least a three-star rating.

The rating of an installer can be:

- Average (three stars)
- Good (four stars)
- Excellent (five stars)

Installer-Customer Collaboration

Depending on the working style of the installer, their level of interaction with customers can be:

- Independent (requires limited input from customer)
- Moderately collaborative (requires some input from customer)
- Collaborative (works closely with customer)

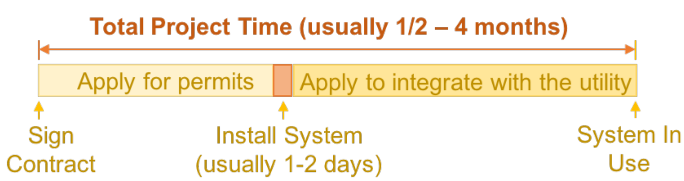
Equipment Technology

Different installers provide equipment with different brands and modules. The equipment can be categorized by the technology they use:

- Cutting-edge technology (on the market for half a year or less)
- Standard technology (on the market for at least 2 years)
- Traditional technology (on the market for at least 5 years)

Total Project Time

The project time from the signing of a contract with the installer to being able to use your solar panels can vary from weeks to months. This includes the time spent applying for permits, setting up equipment, and integrating your system into public utility grids.



Project timeline

Depending on the installer, the total project time can range from:

- 1/2 month
- 1 month
- 2 months
- 4 months

Warranty

A solar system is expected to work for 20-30 years. If a system fails unexpectedly during the time period covered by the warranty, the installer will repair it free of charge. Depending on the installer, the warranty can be:

- 5 years
- 15 years
- 25 years

Savings In 25 Years

This is the percent savings in electricity over 25 years with solar, compared to what you would pay your utility company without solar. *This percent savings already takes into consideration the cost of installing the solar system. If the system is purchased up front, the cost is distributed over 25 years.*

The savings tend to be lower with more advanced equipment and longer warranties since they are usually more expensive. However, depending on a variety of factors, such as the equipment you choose, the price the installer offers, the way you finance the project and so on, the savings can vary:

- 10%
- 25%
- 40%
- 55%
- 70%

Solar System

Imagine you have selected your solar installer. After inspecting your roof, the installer recommends several solar systems and asks you to choose the one you prefer.

As before, in the next section you will first read seven pages of information that can help you to make educated decisions when choosing solar systems. **Please spend enough time on each page to read them carefully (again, the survey will not allow you to proceed if you spend too little time on each page)**. After that, you will be given some questions to answer.

A solar system converts sunlight into electricity. The two major components of a solar system are:

- Solar panels, which convert sunlight to direct current (DC) electricity
- Inverters, which convert the DC electricity produced by panels into alternative current (AC), which can be used directly by household appliances

Below is an example of a solar system. Explanations of each feature are on the following pages.

	Example System
Panel Efficiency	18% efficiency
Panel Visibility	High visibility
Inverter Type	Central inverter
Failures in First Five Years	2 failures
Environmental Benefits	3 acres of forest
Savings in 25 Years	40% savings

Panel Efficiency

This is the percentage of sunlight power that a panel can convert to electricity. To produce the same amount of energy, you will need fewer high-efficiency panels than low-efficiency panels.

Five options for panel efficiency:

- 15.5% (low)
- 18.0%
- 20.5% (medium)
- 23.0%
- 25.5% (high)

To produce the same amount of electricity as 18 low efficiency panels, you will need 14 medium efficiency panels, or 12 high efficiency panels. If your roof is small, you may want higher efficiency panels to fit into the limited space. High efficiency panels can also leave more roof space for system expansion in the future.

Panel Visibility On Roof

Depending on the colors and styles of the solar panels, they may be more or less visible on a roof. Here are two common scenarios:

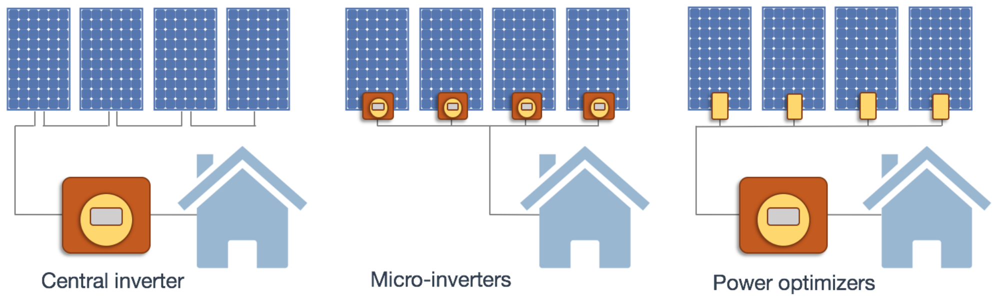
- High visibility - panels visually contrast with roof
- Low visibility - panels visually blend in with roof

Inverters

Inverters convert energy produced by solar panels into electricity that can be used directly by household appliances. There are three options for inverters:

- Central inverter - one inverter connects a group of panels.
- Micro-inverter - each panel has its own inverter.
- Power optimizer - a compromise between central and micro inverters. One inverter connects a group of panels but each panel has its own power optimizer.

If one solar panel in a system is broken or is shaded by a tree, a central inverter will prevent all other panels from working, while micro-inverters will allow other panels to continue operating at full power, and a power optimizer will allow other panels to keep working but with slightly lower efficiency.



Failures In First Five Years

Due to manufacturing defects and other unexpected conditions such as bad weather, a solar system may break down every so often. Different solar systems can have different numbers of failures in the first five years:

- 0 failures
- 1 failure
- 2 failures
- 3 failures

Environmental Benefits

Solar systems emit much less carbon dioxide (CO_2) when generating electricity compared to fossil fuels and thus can provide significant environmental benefits. The reduction of CO_2 emissions of a solar system each year can be converted to the equivalent area of a forest that absorbs the same amount of CO_2. Different solar systems can have different forest area equivalents from 3 to 9 acres of forest.

- 3 acres of forest
- 6 acres of forest
- 9 acres of forest

Savings In 25 Years

This is the percent savings in electricity over 25 years with solar, compared to what you would pay your utility company without solar. *This percent savings already takes into consideration the cost of installing the solar system. If the system is purchased up front, the cost is distributed over 25 years.*

The savings tend to be lower with higher efficiency panels and more reliable equipment since they are usually more expensive. However, depending on a variety of factors, such as the equipment you choose, the price the installer offers, the way you finance the project and so on, the savings can vary:

- 10%
- 25%
- 40%
- 55%
- 70%

APPENDIX II Discrete Choice Analysis with HB Models

Appendix Table 1 Estimated part-worths of HB models

	Installer			System	
	Mean (se)	**St Dev (se)**		**Mean (se)**	**St Dev (se)**
None	-1.008 (0.116)	4.035 (0.111)	None	-0.748 (0.117)	4.236 (0.120)
Reviewer Rating: 3 stars	-1.429 (0.038)	1.016 (0.039)	Efficiency: 15.5%	-0.902 (0.037)	0.912 (0.048)
Reviewer Rating: 4 stars	0.294 (0.022)	0.457 (0.026)	Efficiency: 18.0%	-0.470 (0.032)	0.608 (0.041)
Collaboration Style: Independent	-0.232 (0.021)	0.464 (0.027)	Efficiency: 20.5%	0.216 (0.034)	0.374 (0.033)
Collaboration Style: Moderately Collaborative	0.076 (0.018)	0.287 (0.021)	Efficiency: 23.0%	0.531 (0.029)	0.542 (0.036)
Technology: Cutting-Edge	0.206 (0.026)	0.751 (0.029)	Visibility: High	-0.306 (0.024)	0.771 (0.025)
Technology: Standard	-0.014 (0.023)	0.459 (0.028)	Inverter: Central	-0.737 (0.036)	1.098 (0.040)
Project time: 1/2 month	0.258 (0.025)	0.461 (0.034)	Inverter: Micro	0.548 (0.033)	1.076 (0.034)
Project time: 1 month	0.275 (0.024)	0.349 (0.026)	Failures: 0	1.530 (0.048)	1.542 (0.048)
Project time: 2 months	-0.006 (0.019)	0.313 (0.026)	Failures: 1	0.714 (0.026)	0.500 (0.032)
Warranty: 5 years	-1.834 (0.047)	1.327 (0.045)	Failures: 2	-0.604 (0.026)	0.612 (0.032)
Warranty: 15 years	0.432 (0.024)	0.464 (0.029)	Environmental Benefit: 3 acres of forest	-0.459 (0.026)	0.662 (0.032)
Savings: 10%	-3.440 (0.079)	2.109 (0.072)	Environmental Benefit: 6 acres of forest	0.136 (0.02)	0.259 (0.023)
Savings: 25%	-0.954 (0.037)	0.846 (0.041)	Savings: 10%	-3.830 (0.093)	2.611 (0.085)
Savings: 40%	0.480 (0.03)	0.425 (0.038)	Savings: 25%	-0.920 (0.039)	0.976 (0.043)
Savings: 55%	1.152 (0.043)	0.877 (0.038)	Savings: 40%	0.586 (0.029)	0.442 (0.038)
			Savings: 55%	1.358 (0.045)	1.105 (0.048)
Log-likelihood	-11598.22		Log-likelihood	-10394.01	

Note: the log-likelihoods were calculated at the mean individual-level coefficients across iterations.

APPENDIX III Interactions Between Respondent Demographics and Attribute Preferences

Linear utilities instead of part-worth utilities were estimated for continuous attributes for two reasons: firstly, the previous HB modeling results demonstrated that the part-worth utilities of these attributes had linear trends; secondly, the inclusion of interaction terms largely increased the models' number of explanatory variables, and estimating linear utilities for continuous variables helped simplify the models and prevent overfitting. The results are summarized in Appendix Table 2.

Besides the interaction effect discussed in the main text, it was also found that the interaction effect between cutting-edge technology and household income was significant and positive, the interaction between independent collaboration style and state was significant and positive, and the interaction between savings and state was significant and negative. These suggest that higher income homeowners tended to prefer more cutting-edge technology compared to lower income homeowners. Massachusetts homeowners had stronger preference for installers working collaboratively than independently compared to California homeowners did. And California homeowners cared a little less about savings compared to Massachusetts Homeowners.

The "None" option significantly and positively interacted with respondents' age, income and solar ownership. Older homeowners, higher income homeowners, and current solar adopters tended to choose "none" more frequently compared to younger homeowners, lower income homeowners, and non-adopters.

Type of inverter had significant interaction effects with age and state: older homeowners had stronger preferences for micro-inverters and lower preference for central inverters compared to younger homeowners. Massachusetts homeowners had lower preference for central inverters compared to California homeowners. Significant interactions between solar systems' environmental benefit and state and solar ownership indicate that Massachusetts homeowners and solar adopters on average cared more about the environmental benefit of a solar system, compared to California homeowners and non-adopters respectively. Again, the "none" option had significant interaction effects with age; older homeowners were more likely to choose "none" compared to younger homeowners.

Appendix Table 2 Coefficient estimations with interactions effect

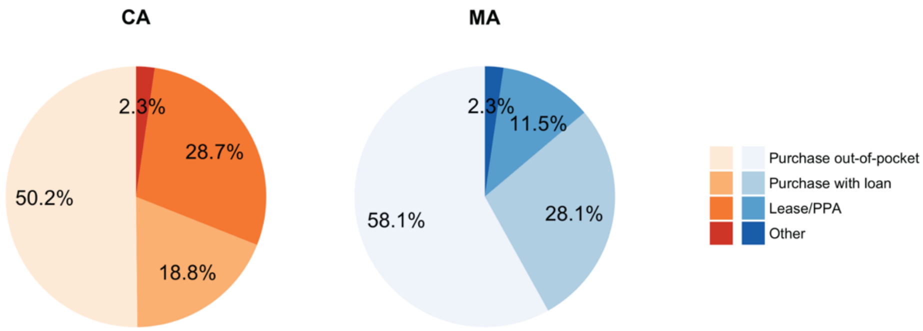
	Installer					System			
	β	**se**	**t-value**	**p-value**		***β***	**se**	**t-value**	**p-value**
None	-0.165	0.019	-8.669	< 0.001***	None	-0.016	0.018	-0.891	0.373
Reviewer Rating	0.652	0.012	56.208	< 0.001***	Efficiency	0.076	0.003	27.548	< 0.001***
Collaboration - Independent	-0.139	0.013	-10.330	< 0.001***	High visibility	-0.135	0.009	-14.938	< 0.001***
Collaboration - M Collaborative	0.049	0.013	3.713	<0.001***	Inverter – Central	-0.333	0.013	-25.369	< 0.001***
Technology - Cutting edge	0.148	0.013	11.411	<0.001***	Inverter – Micro	0.258	0.012	21.483	<0.001***
Technology - Standard	0.000	0.013	0.014	0.989	Failures	0.496	0.009	57.281	<0.001***
Project time	-0.123	0.007	-16.876	<0.001***	Environmental benefit	0.077	0.004	21.173	< 0.001***
Warranty	0.077	0.001	62.714	<0.001***	Savings	0.045	0.001	70.486	< 0.001***
Savings	0.050	0.001	74.517	<0.001***					
Interactions									
Age					**Age**				
× None	0.520	0.018	28.385	< 0.001***	× None	0.434	0.017	25.889	<0.001***
× Reviewer Rating	-0.017	0.011	-1.623	0.105	× Efficiency	-0.005	0.003	-2.042	0.041*
× Collaboration - Independent	-0.021	0.012	-1.711	0.087	× High visibility	-0.056	0.008	-6.722	<0.001***
× Collaboration - M Collaborative	-0.012	0.012	-1.016	0.310	× Inverter - Central	-0.074	0.012	-6.168	<0.001***
× Technology - Cutting edge	-0.013	0.012	-1.070	0.285	× Inverter - Micro	0.074	0.011	6.708	<0.001***
× Technology - Standard	0.005	0.012	0.417	0.677	× Failures	0.011	0.008	1.334	0.182
× Project time	-0.021	0.007	-3.177	0.001**	× Environmental benefit	-0.004	0.003	-1.287	0.198
× Warranty	0.014	0.001	12.220	< 0.001***	× Savings	0.001	0.001	1.272	0.204
× Savings	0.000	0.001	-0.361	0.718					
Income					**Income**				
× None	0.109	0.018	6.053	< 0.001***	× None	0.019	0.017	1.137	0.256
× Reviewer Rating	0.040	0.011	3.631	< 0.001***	× Efficiency	0.001	0.003	0.293	0.769
× Collaboration - Independent	-0.009	0.013	-0.675	0.500	× High visibility	-0.051	0.009	-5.887	<0.001***
× Collaboration - M Collaborative	0.001	0.012	0.042	0.966	× Inverter - Central	-0.007	0.012	-0.539	0.590
× Technology - Cutting edge	0.043	0.012	3.487	< 0.001***	× Inverter - Micro	0.013	0.011	1.095	0.274
× Technology - Standard	-0.011	0.013	-0.909	0.363	× Failures	-0.004	0.008	-0.535	0.593
× Project time	0.010	0.007	1.509	0.131	× Environmental benefit	-0.004	0.003	-1.211	0.226
× Warranty	0.001	0.001	0.546	0.585	× Savings	0.002	0.001	2.895	0.004**
× Savings	0.001	0.001	1.183	0.237					
State					**State**				
× None	-0.017	0.017	-0.990	0.322	× None	-0.013	0.016	-0.833	0.405
× Reviewer Rating	-0.006	0.011	-0.515	0.606	× Efficiency	0.002	0.003	0.868	0.385
× Collaboration - Independent	0.053	0.012	4.258	< 0.001***	× High visibility	0.019	0.008	2.257	0.024
× Collaboration - M Collaborative	-0.030	0.012	-2.491	0.013*	× Inverter - Central	0.045	0.012	3.643	<0.001***
× Technology - Cutting edge	0.024	0.012	2.018	0.044*	× Inverter - Micro	-0.030	0.011	-2.696	0.007
× Technology - Standard	-0.035	0.012	-2.812	0.005**	× Failures	0.006	0.008	0.803	0.422
× Project time	-0.009	0.007	-1.404	0.160	× Environmental benefit	-0.018	0.003	-5.209	<0.001***
× Warranty	0.000	0.001	-0.130	0.897	× Savings	-0.001	0.001	-2.396	0.017
× Savings	-0.004	0.001	-6.079	< 0.001***					
Solar					**Solar**				
× None	0.105	0.019	5.469	< 0.001***	× None	0.035	0.018	1.978	0.048
× Reviewer Rating	-0.034	0.012	-2.828	0.005**	× Efficiency	0.003	0.003	0.979	0.328
× Collaboration - Independent	-0.019	0.014	-1.362	0.173	× High visibility	0.059	0.009	6.255	<0.001***
× Collaboration - M Collaborative	0.018	0.014	1.297	0.195	× Inverter - Central	0.039	0.014	2.844	0.004
× Technology - Cutting edge	0.008	0.013	0.584	0.559	× Inverter - Micro	-0.027	0.013	-2.146	0.032
× Technology - Standard	0.021	0.014	1.511	0.131	× Failures	-0.010	0.009	-1.100	0.271
× Project time	0.015	0.008	1.937	0.053	× Environmental benefit	0.017	0.004	4.526	<0.001***
× Warranty	0.003	0.001	2.218	0.027*	× Savings	0.001	0.001	1.898	0.058
× Savings	0.001	0.001	1.722	0.085					
	No interactions		With interactions			No interactions		With interactions	
Log-likelihood	-30704		-30036			-32958		-32453	
AIC	61426		60162			65932		64986	
BIC	61500		60533			65998		65316	

Notes: Effect coding was used to categorize demographic variables: California was coded as 1 and Massachusetts was coded as -1; a solar adopter was coded as 1 and a non-adopter was coded as -1. Income was treated as a continuous variable and was normalized to center at 0. These made sure that the estimates of the model main effect would still represent the average preferences of the population. Responses to income and age questions that were "not prefer to answer" were replaced with the median values of the population. * denotes a statistically significant interaction effect for $p < 0.05$, ** for $p < 0.005$, and *** for $p < 0.001$.

APPENDIX IV Solar Adopters' Experience in Installing Solar PV Systems

This section summarizes additional results of solar adopters' experiences in installing solar PV systems.

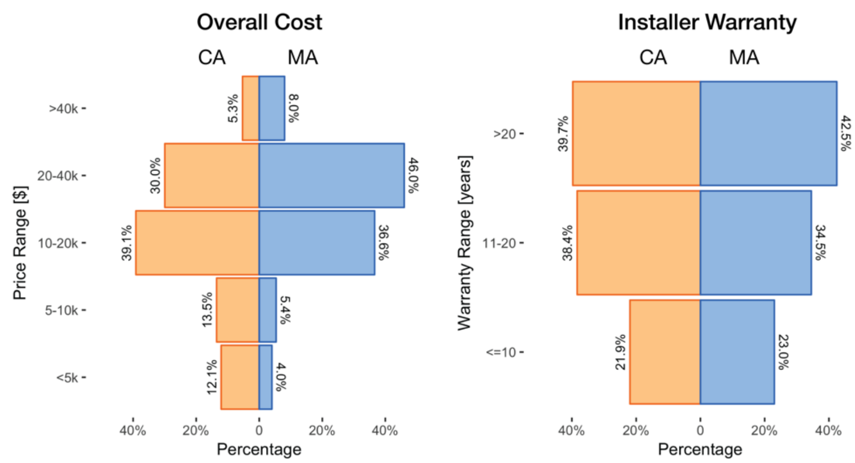
Financing, Price, and Warranty. Appendix Figure 1 shows the distributions of types of financing solar adopters used. Purchasing out-of-pocket was the most popular financing option in both states. Fewer solar adopters in California purchased with a loan. More Californians chose leasing or a Power Purchase Agreement (PPA) compared to solar adopters in Massachusetts.



Appendix Figure 1 Financing options chosen by solar adopters

The distributions of the overall cost of installing solar PV systems (including hardware, labor and permitting) after rebates (such as a tax credit) are presented in Appendix Figure 2. Since the payment methods were more diverse for systems that were financed through leasing or PPA (i.e. paying a fixed monthly rent, paying for the electricity produced by the system, or pre-paid for the solar system upfront), only the cost of the systems that were purchased (either out-of-pocket or with loan) was included here. The cost of solar was overall lower in California compared to Massachusetts. The chi-squared test showed that the difference was statistically significant (chi-squared = 25.182, df=4, p-value <0.001***).

The distributions of warranty length are also summarized in Appendix Figure 2. Around 40% of systems were covered by a 20+ year warranty in both states. The distributions were not significantly different between the two states (chi-squared = 0.8625, df = 2, p-value = 0.650).



Appendix Figure 2 Distributions of the overall cost of purchased solar systems after rebates (left); distributions of installer warranty (right)

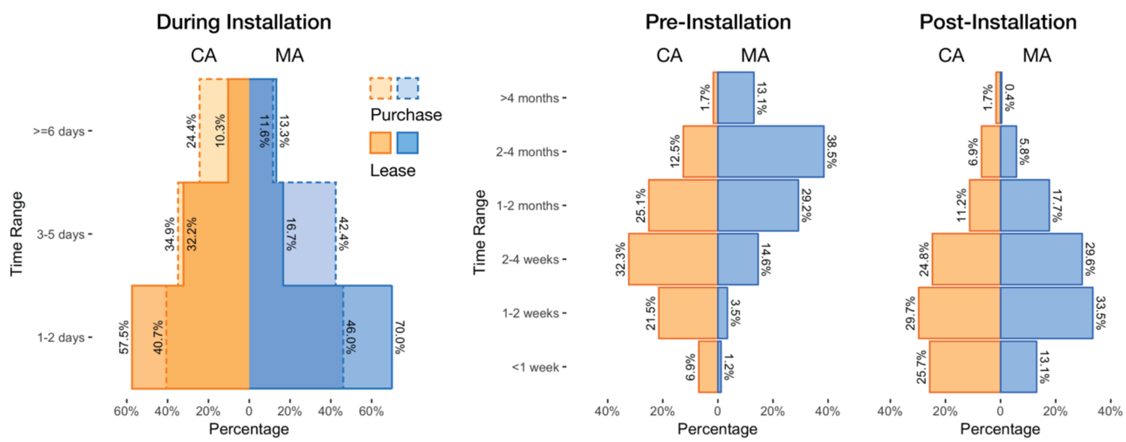
Solar Installation Process.

Appendix Figure 3 shows the time spent on different phases of solar installation: pre-installation (the time from a homeowner signing a contract with an installer to the solar panels being installed; installers use this time to apply for permits and prepare materials for the project), during installation (the actual installation of the system, including mounting the panels on roof, wiring the inverters, etc.), and post-installation (time for utility companies to interconnect the system to the power grid and for government agencies to inspect the system, from installing a system to solar adopter being able to use the system).

The installation phase tended to be short. Almost half of the solar adopters had their systems installed in less than two days. Those who leased had their systems installed even faster compared to those who purchased in both states (California: chi-squared = 9.926, df = 2, p-value = 0.007**; Massachusetts: chi-squared = 5.1847, df = 1, p-value = 0.023*). Massachusetts solar adopters who purchased appeared to have significantly shorter installation time compared to California solar adopters who purchased (chi-squared = 12.299, df = 3, p-value = 0.006**). No significant differences between those who leased in the two states were detected.

No significant differences between the pre-installation and post-installation phases were detected between solar adopters who purchased or leased the system. The overall distributions are plotted in Appendix Figure 3

. The post-installation phase was longer than the actual installation phase. Around half of solar adopters were able to use their systems within two weeks after installation. The post-installation phase was longer in Massachusetts than in California (chi-squared = 18.367, df = 4, p-value = 0.001**). Overall, the pre-installation phase took the longest time, and was significantly longer in Massachusetts than in California (chi-squared = 129.24, df = 4, p-value < 0.001***). This was likely due to local weather conditions. In Massachusetts, installers would sign contracts in winter or early spring but would need to wait until later in the year to be able to install the system. Other factors that could delay the installation include group purchasing programs (such as Solarize Massachusetts [51]), during which installers would spend a few months to identify customers, and then install all of the systems in a concentrated period of time.



Appendix Figure 3 Time spent on different phases of solar installation