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Factors Influencing Household Solar Adoption in Santiago, Chile

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Abstract: In Santiago, Chile, the market conditions are seemingly excellent for the household adoption of photovoltaic (PV) technology, yet the uptake is negligible. To explore this paradox, the authors conducted a Delphi study to solicit the knowledge of a panel of Chilean PV experts. These efforts yielded 26 factors—both motivations and barriers—impacting the diffusion of PV in Santiago. Of the 26, experts were in consensus on the relative importance of 21. The literature suggests that diffusion of PV technologies is influenced by complex technical, economic, and social factors. Similarly, the experts saw influence from financial, environmental, and energy supply (e.g., electrical reliability) factors. They saw emergent barriers to adoption as being financial, technical, institutional, and knowledge factors. They considered the most important factors influencing adoption to be financial motivations (e.g., subsidies) and financial barriers (e.g., high upfront costs); they considered the least important factors to be environmental motivations (e.g., environmental stewardship) and technical barriers (e.g., concerns with roof mounting). With this knowledge, the authors develop an adoption framework for household PV that describes the interaction among the identified motivations and barriers. This framework informs policy recommendations for Santiago, Chile, and contributes to the body of literature exploring the interconnected systems of factors that influence civil infrastructure in general and PV adoption in particular.

Author keywords: Adoption; Diffusion; Household solar; Photovoltaic (PV); Chile; Barriers.

Introduction

In Latin America, one of the leaders in adopting large-scale renewable energy is Chile. Since 2001, Chile has invested US$208 million in hydroelectric technologies (IRENA 2015). In 2010, Chile reaffirmed its motivation to decrease carbon emissions so as to decrease climate change by becoming a member of the Organization for Economic Corporate Development (OECD). Since then, Chile has continued to incentivize renewable energy. Recently, for example, its Ministry of Energy articulated the country's goal to lift barriers to entry of competitive renewable energy technologies by 2020 (Chilean Ministry of Energy 2014). The ministry also proposed having 45% of the country's energy sourced from nonconventional renewable energy technologies by 2025.

Hence, the government has demonstrated political impetus to adopt solar energy, and the country possesses favorable economic, social, and technical characteristics that are known to stimulate adoption. For example, many households within the Santiago context enjoy high incomes (Rai and McAndrews 2012) and possess a keen awareness of and experience with fossil fuel–induced air pollution (Cáceres et al. 2014; Rai and McAndrews 2012; Zhang et al. 2011). Residents also have high daily global horizontal irradiance (GHI) averages of approximately 5.1 kWh/m^2 (Escobar et al. 2014), an existing net-billing law that enables households to sell excess energy (Watts et al. 2015), and are subject to increasing vulnerability to volatility in energy prices (Chilean Ministry of Energy 2012; Grágeda et al. 2016). All these factors, according to the literature, are supportive of wide residential uptake of solar technology.

And yet, residential solar photovoltaic (PV) use within Santiago is surprisingly scarce. A 2016 request for information from the Santiago municipal government found that, within the city limits, only 22 households have legally installed PV technology (SECa 2016). These PV systems, being within the city, are registered with the local electrical utility and thus eligible to receive benefits thanks to the existing net-billing law. This raises an important question. Why have domestic installations of solar PV in Santiago—in spite of its favorable context, nationwide awareness of, and policy attention to renewable energy—failed to flourish?

Barriers to the spread of PV technologies are described in the literature. The barriers confronting Santiago could be varied; among the physical, environmental, and financial uncertainties (Shakouri et al. 2017), barriers could include the following: a lack of governmental subsidies and incentives (IRENA 2015; Beck and Martinot 2012; Margolis and Zuboy 2006; Sovacool 2009; Zhang et al. 2011), a relatively new and slowly maturing net-billing scheme for excess power generation (Ley 20.571 2014; Watts et al. 2015), slow and conventional organizational constructs (Yuventi et al. 2013), as well as minimal technical standards and certifications (IRENA 2015; Beck and Martinot 2012; Margolis and Zuboy 2006). However, no research has been conducted to explicitly investigate the factors that influence domestic solar PV adoption in Santiago, and certainly no research has leveraged local expert knowledge.

This latter point is important. Previous literature on domestic PV diffusion has shown that barriers and enablers tend to go beyond technical and policy advancement (Popp et al. 2011; Sovacool 2014), and instead reside at the intersection of social, economic,

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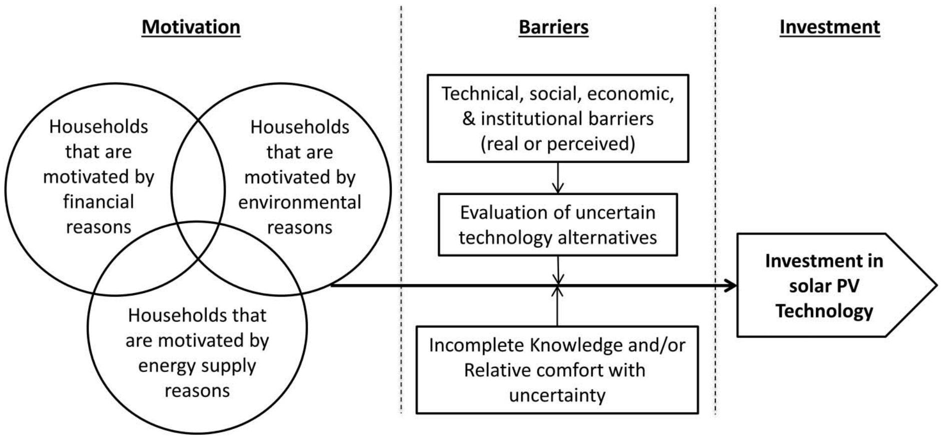

Fig. 1. Conceptual framework of the drivers of domestic solar PV adoption based on the literature; bold arrow represents a household's progression from motivation toward investment in solar PV technology

and technical context. In Senegal, for example, Thiam (2011) demonstrated the importance of social acceptance of renewable technologies. Some researchers (Faiers and Neame 2006; Margolis and Zuboy 2006) have observed that adoption has been thwarted by consumer perceptions of solar-panel aesthetics. Residents considering adopting solar panels have also been influenced by other peer-related effects (Richter 2014), such as convincing conversations between neighbors and solar PV owners (Bollinger and Gillingham 2012; Rai et al. 2016; Rai and Robinson 2013), resulting in solar-panel owners being clustered together (Graziano and Gillingham 2015).

Another key role in diffusion may also be played by consumer knowledge. Customers were strongly influenced, for example, by their ignorance of PV technology, including issues related to permitting, planning, and maintaining it over its lifecycle (Beck and Martinot 2012). This same barrier has been shown to influence installers and distributers, who may not always possess the relevant technical information and skills (Margolis and Zuboy 2006; Beck and Martinot 2012). Some studies have identified sociotechnical barriers. That is, some consumers disregard renewable energy sources because they do not know of its economic benefits or of their own energy consumption, or because their paradigms of permissible energy sources point them to traditional fossil-fuel power plants (Margolis and Zuboy 2006; Sovacool 2009).

Whether consumers adopt solar panels is also influenced by socioeconomic barriers. They perceive some financial risk and are hesitant to invest in solar PV, a hesitance reinforced by the relatively high capital costs of installation (Faiers and Neame 2006; Margolis and Zuboy 2006; Rai et al. 2016). These issues may even be exacerbated by competing energy providers who offer subsidies for fossil fuels (Beck and Martinot 2012; Faiers and Neame 2006; Popp et al. 2011; Rai and McAndrews 2012). Consumers must also contend with their own lack of trust in available information on PV (Rai and Robinson 2013), uncertainty of the costs associated with operation and maintenance (Rai et al. 2016), and the long timeline for return on investment (ROI) (Rai et al. 2016; Rai and McAndrews 2012). Studies have shown that, as a result of financial challenges, consumers must see that the present value of a PV investment greatly exceeds the investment cost by a factor that can surmount consumer uncertainty (Bauner and Crago 2015). All these uncertainties lead to mainstream consumers putting off the adoption of PV until market and policy maturity reach a satisfactory level of perceived risk, known as the optional value (Bauner and Crago 2015).

This research thus seeks to inform maturing policy interventions promoting domestic solar PV systems in Chile. In addition, it contributes to the broader body of knowledge on the topic of residential solar PV diffusion. This study is guided by two overarching research questions:

- What factors are preventing the adoption of household solar technologies in Santiago?
- Of these factors, which are the most influential?

To answer these questions, a Delphi panel of experts was used to elicit and evaluate the local importance of factors.

The factors and literature referenced earlier informs a conceptual framework for households' energy-technology decisions (Fig. 1). In this framework, energy-technology choices are driven by some combination of the following motivations: financial (e.g., governmental subsidies or incentives), environmental (e.g., desire for environmental stewardship), and energy supply (e.g., preferring independence from the grid). These motivations exist in the context of incomplete knowledge and institutional, financial, and technical challenges that act as potential barriers to adoption (or moderating variables) (Baron and Kenny 1986). Depending on the collective strength of the financial, environmental, and energy-supply motivations, households are more or less willing to accept the various real and perceived uncertainties [i.e., ROI timeline, operation, and maintenance (O&M) costs]. As prior work has shown (Kaminsky 2016), energy-technology choice is also driven by collective levels of (dis) comfort with uncertainty.

The conceptual framework used to structure the Delphi questionnaire is shown in Fig. 1. This framework is described in the "Methods" section and was used to analyze the expert panel's collective knowledge of household PV in Santiago.

Methodology

The Delphi method (Helmer-Hirschberg 1967; Hallowell and Gambatese 2010; Linstone and Turoff 2002) is a structured process for gathering expert knowledge on complex topics that are otherwise difficult to study. In this method, experts are asked to independently and iteratively indicate the importance of a set of factors that are believed to be relevant to a research question. In the current study, this was done by asking experts to indicate the importance of factors on a series of questionnaires, using a five-step anchored Likert scale, with 1 = not important, 2 = somewhat important, 3 = neutral, 4 = important, and

5 = very important. After each questionnaire iteration, a consensus score was calculated for each factor to determine whether or not the expert panel had reached agreement on the relative importance of that particular factor. As described next, experts were asked to reconsider all factors that dis not reach consensus in an additional questionnaire. Consensus is defined as a factor with the interquartile range (IQR) of Likert scores being equal to or less than 1 (Raskin 1994; von der Gracht 2012). In order to capture reasons for the differing scores, factors that had a range of expert Likert scores equal to or greater than 3 were presented to the experts in subsequent rounds.

When consensus was reached, the factor was removed from further questionnaire rounds, thus reducing the burden on the experts. If consensus was not reached, the experts were asked to reconsider their previous responses while also viewing aggregated median scores from the entire panel. During these subsequent questionnaire iterations, experts were also asked to provide written comments to indicate why they agreed or disagreed with the group score. This provided the researchers with information regarding the importance and interpretation of each factor as well as details on why experts disagreed on contentious factors.

After approval from Chilean and U.S. Human Subjects in Research boards, the first step in data collection was to establish criteria for the identification of experts. The final criteria are given in Table 1; to qualify as an expert for this study, candidates needed to score three points.

Once these criteria were established, an initial list of experts was generated and validated against the criteria. Next, the Dean of Engineering at the Universidad Diego Portales e-mailed each of the experts to invite them to participate in the study. The dean contacted, in total, 11 experts. Of these, eight agreed to participate, with all of them ultimately participating in the four questionnaire rounds. The distribution of experts included individuals who worked within government agencies (two experts), academia (two experts), and consulting (four experts). Each questionnaire was written in Spanish and electronically distributed using the SurveyGizmo platform. The first questionnaire round asked each expert to brainstorm factors that might influence the spread of household solar technology in Santiago. Subsequently, each expert was presented with a list of potential factors drawn from the academic literature (Table 2) and was asked to indicate if they felt these were relevant (or irrelevant) to the Santiago context. This supplemental list was provided to allow experts to confirm or discard factors previously identified in the literature.

Once the first questionnaire round was complete, the research team compiled a list of all factors that at least one expert had

Table 1. Criteria for Qualification of Experts

Points[a]	Criterion
3	First or second author on an academic article treating the planning, implementation, regulation, or development of photovoltaic technology in Santiago, Chile
1 per article, up to 3	First or second author on an academic article treating the planning, implementation, regulation, or development of energy systems in Chile
1 per article, up to 2	First or second author on nonacademic publication treating the planning, implementation, regulation, or development of energy systems in Chile
1	Member or president of a national committee considering the planning, implementation, regulation, or development of renewable energy in Chile
3	More than 5 years of professional experience in the regulation and policy of photovoltaic technology in Santiago
2	3–5 years of professional experience in the regulation and policy of photovoltaic technology in Santiago
1	1–3 years of professional experience in the regulation and policy of photovoltaic technology in Santiago
3	More than 5 years of professional experience in the planning, implementation, regulation, or development of photovoltaic technology in Santiago
2	3–5 years of professional experience in the planning, implementation, regulation, or development of photovoltaic technology in Santiago
1	1–3 years of professional experience in the planning, implementation, regulation, or development of photovoltaic technology in Santiago
2	At least 3 years of professional experience in the energy industry in Santiago
1	M.S., MA, or Ph.D. in the field of engineering, sociology, or economics
2	Presentation at a conference treating the planning, implementation, regulation, or development of energy systems in Santiago

[a]Three points needed for inclusion in this study.

Table 2. List of Factors from Literature Presented to the Experts in the First Round

Factor	Definition
Energy independence	Importance to customers of generating their own household electricity to remain independent from the grid
Environmental stewardship	Importance to customers to protect the environment by installing solar panels on their house
Energy reliability	Importance to customers of having access to reliable electricity
Return on investment	Importance to customers to eventually pay off their PV technology and begin saving money
Energy price increases	Importance to customers to be isolated from variable electricity prices
Access to solar distribution companies	Importance for customer of access to distribution companies
Governmental regulation	Importance of national construction regulations and norms
Knowledge of PV options	Importance of customers to know the different options for solar PV
Perceptions of technology	Importance of customer perception of technology development and overall quality
Ability to cover installation costs	Importance for customers to be able to pay the high initial construction costs
Solar-panel aesthetics	Importance to customers for the solar panels to look good on their house

Table 3. Factors and Results

Factor category	Number	Factor name	Definition	Score (median/IQR)	Consensus
			Expert panel identified motivations		
Financial motivation	2	Initial subsidies	Existence of financing/subsidies to cover initial investment costs	4.0/0.25	Yes (Round 3)
Energy-supply motivation	25	Energy reliability	Households use PV to ensure consistent supply of electricity in case the grid fails	3.0/1.0	Yes (Round 4)
Energy-supply motivation	26	Energy independence	Households prefer to produce their own energy rather than have it generated by the government	3.0/1.5	No consensus reached
Financial motivation	23	Energy cost	Price of normal grid electricity is affordable enough	3.0/0.25	Yes (Round 3)
Environmental motivation	22	Environment	Households desire to help the environment	2.5/1.0	Yes (Round 4)
			Expert panel identified barriers		
Financial barrier	1	Initial investment	High installation costs, hard to recuperate/long payback period	4.5/1.0	Yes (Round 2)
Incomplete knowledge	6	Cost comparison	Difficulty for households to find information necessary to compare costs between different PV systems and installers	4.5/1.0	Yes (Round 3)
Financial barrier	20	Price variation	Wide dispersion of PV technology/installation process, and associated price variations	4.0/0.0	Yes (Round 4)
Financial barrier	21	Uncertain ROI	Uncertainty regarding return on investment	4.0 (range of 3)	No consensus reached
Incomplete knowledge	3	Technology information	Low of knowledge about existence of PV systems, or on how they operate, as well as the different actors involved in the process: clients, installers, distributors, etc.	4.0/0.5	Yes (Round 3)
Incomplete knowledge	5	Pros/cons of PV	Lack of household knowledge regarding the benefits or costs of PV	4.0/1.0	Yes (Round 2)
Incomplete knowledge	17	Evidence of success	Low numbers of successful residential solar PV installations people can see	4.0/0.25	Yes (Round 4)
Institutional barrier	9	Knowledgeable companies	Lack of knowledgeable PV consulting/distribution/installation companies	4.0 (range of 3)	No consensus reached
Institutional barrier	10	Market maturity	Scarcity/paucity of attractive offers/promotions/campaigns provided to potential buyers	4.0/0.5	Yes (Round 4)
Institutional barrier	14	Ley 20.571: Knowledge of benefits	Erroneous or hard-to-find information on how to interpret the benefits of excess energy sold back to the grid based on the law	4.0/1.0	Yes (Round 4)
Technical barrier	7	Installation quality	Lack of access to quality materials or installation practices; uncertainty of quality	4.0/ 0.25	Yes (Round 2)
Technical barrier	11	Energy supply and demand timing	Daily variations in the available supply of solar electricity do not match the timing of demand	4.0(range of 3)	No consensus reached
Institutional barrier	13	Ley 20.571: Complexity	Existing net-billing framework is difficult to understand and engage with	3.5/1.25	No consensus reached
Institutional barrier	15	Postsale service	Nonexistent postsale service from the provider for proper O&M by user, throughout the service lifecycle	3.5/1.0	Yes (Round 2)
Incomplete knowledge	8	Maintenance	Lack of household knowledge on proper maintenance	3.0/1.0	Yes (Round 2)
Incomplete knowledge	19	Education	Lack of workshops, seminars, and events for users such as free workshops, vendor conventions, and tools for energy production simulation	3.0/0.25	Yes (Round 4)
Technical barrier	12	Roof mounting	Roof mounting can damage the client's roof and cause leaks into the house	3.0/0.5	Yes (Round 3)
Technical barrier	16	Building shading	Shade produced by tall buildings can have a negative effect on PV energy production	3.0/0.5	Yes (Round 2)
Technical barrier	24	Aesthetics	Homeowners think solar PV systems make their house look ugly	3.0/1.0	Yes (Round 2)
Technical barrier	4	Pollution	Pollution in Santiago creates a film that can negatively influence PV module performance	2.0/0.5	Yes (Round 3)
Technical barrier	18	Nontracking systems	Most systems are nontracking (static) and do not fully take advantage of solar radiation	2.0/1.0	Yes (Round 3)

identified as important to the Santiago context (Table 3). In a second questionnaire round, this list of factors was used to have experts indicate the relative importance of each factor on a five-point Likert scale (as detailed earlier). After the second questionnaire, consensus was reached on seven factors, all of which were removed from subsequent rounds. The third and fourth questionnaire rounds, following Delphi protocol, showed experts three things—the remaining factors, the score the expert had provided on the previous round, and the median score from the aggregated group responses of the previous round. This is done as part of an attempt to reach consensus on the remaining factors. Each expert was asked to reconsider the score they had previously provided and then write a comment explaining why they changed or declined to change their answer.

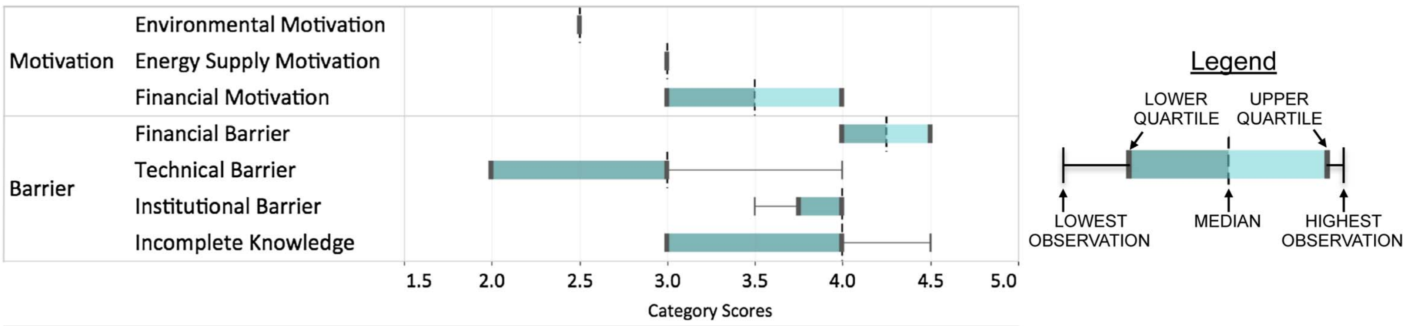

Fig. 2. Box and whisker plot with range of factor category scores

Study Limitations

The findings of this study are necessarily limited to the knowledge of the experts who agreed to participate. Although the number of experts is within the number recommended for the Delphi method (Hallowell and Gambatese 2010), it is possible that additional panelists would have suggested factors that are not captured here. Similarly, additional panelists could have disagreed with the group and changed the consensus results. To address this latter limitation, researchers used multiple strict criteria for consensus (maximum IQR of 1 and maximum range of expert scores of 3). To capture reasons for the differing scores, researchers in subsequent rounds presented the experts with factors scoring equal to or greater than 3.

In another key limitation, homeowners were not included as experts in this study, despite the fact that they are ultimately the ones making household PV investment decisions. Homeowners were left out because of the logistic difficulty involved in identifying homeowners that have seriously considered but decided against installing PV technology. Furthermore, to include only homeowners who had installed PV systems would problematically bias the findings. In a related point, as just 22 Santiago homes have legally installed PV systems, these households may reasonably be considered innovators (or the very earliest adopters of a new technology). They are unlikely then to be representative of mainstream adopters (or those members of a population who adopt a new technology within one standard deviation of the mean). When adopting new technologies, for example, mainstream adopters are more influenced by cost and existing support systems (Rogers 1983).

Finally, the questionnaires were presented to the experts in Spanish; all translations provided here are the authors'. Although every attempt was made to reflect the content and tone of the experts' comments, some nuances may have been unintentionally lost in translation.

Results and Discussion

After completing the first round of questionnaires, the experts found that homeowners in Santiago considering PV adoption were likely influenced by 26 distinct factors. Among these were 11 factors from the literature (provided in Table 2); these were included in subsequent rounds because at least one of the experts agreed that the factor was relevant. The 26 factors considered in this study can be found in Table 3; 21 of these factors were identified by consensus. In Table 3, motivations and barriers are presented separately, in order of importance per the median Likert score. Table 3 also presents the following information: (1) IQR of the Likert scores with each median Likert score for each factor (presented as Median/IQR); (2) category from the proposed analytic framework (Fig. 1) to which each factor belongs; and (3) whether or not that factor was identified by consensus.

The factors described in Table 3 were organized (for the purposes of this discussion and following the analytic framework proposed in Fig. 1) into the following seven categories: energy-supply motivations, environmental motivations, financial motivations, technical barriers, institutional barriers, financial barriers, and incomplete knowledge. Each of these is discussed subsequently, with the normalized factor score shown in the heading considering only factors that reached consensus.

Fig. 2 plots the factor scores for all factors that were identified by consensus (21 factors). The box plot shows the range of scores in each category, with the change in shade and dashed line indicating the median category score. The gray bands indicate the median-exclusive quartiles, and the whiskers show the maximum and minimum factor scores. Throughout the remainder of the paper, to aid in the analysis and interpretation of factor importance, the results provided in Table 3 are referenced with the following designation [factor identifier, median score, IQR]. For example, Factor 5—pros/cons of PV—would be referenced as [5, 4.0, 1.0].

Environmental Motivations (Normalized Category Score: 2.5)

A single factor in this study [22, 2.5, 1.0] presented the idea that the adoption of household solar systems could be impacted by homeowners' motivations for environmental stewardship (or lack thereof). The expert panel, however, gave this factor one of the lowest median scores (2.5). In other words, most experts felt this was one of the least important factors. One expert mentioned that the environment "is a secondary motivation, and only after the economic benefit is assured." Another panelist indicated that "concern for the environment for users, although not being a decisive factor, is an additional argument for the use of solar." Although the experts reached consensus regarding environmental motivation, they did so at the defined limit of the IQR of expert scores and only during the final questionnaire round. One expert who ranked the environmental motivations more highly than others commented, "[PV] technology is costly, and without tax and other economic incentives, there isn't a real incentive other than the environment driving the implementation of this type of technology."

Energy Supply Motivations (Normalized Category Score: 3.0)

The energy-supply motivations concerned the motivation to have an independent energy supply [26, 3.0, 1.5 (no consensus)] and to have reliable electricity from the grid [25, 3.0, 1.0].

Only one of these factors (energy reliability) was identified by consensus at a median score of 3.0. This suggests that reliable electricity is an important motivator in general, but that in this particular context, "the energy grid in Santiago is reliable." One expert mentioned that

> Many potential users believe that the on-grid systems will assure supply . . . When we explain that this is not so, but that the system will reduce the [electrical] bill, most understand and opt for a normal on-grid system. Only a few invest additional money to have a backup with a battery bank, etc.

This suggests that although many people in Santiago may mistakenly believe that a backup for grid outages is a feature of typical household solar systems, they are not motivated by having the capacity to improve grid reliability. The other factor in this category, energy independence from the grid [26, 3.0, 1.5], was not reached by consensus. This motivation is discussed later along with other factors that were not reached by consensus.

Financial Motivations (Normalized Category Score: 3.5)

In contrast to the energy-supply motivations, experts reached a consensus on both the financial motivation factors, namely initial subsidies [2, 4.0, 0.25] and energy cost [23, 3.0, 0.25]. These two factors scored the highest among the various motivation types (median scores of 4 and 3, respectively). For example, one expert said that "economic performance is always the most important." Even these financial motivations, however, failed to achieve the highest possible score (score of 5). Regarding the highest-scoring factor in this category (subsidies), one expert said that "this isn't all correct; there exist state programs for financing and subsidies, although they are for certain energy rates and periods of use." These policy details are elaborated upon later. In addition, one expert stated that "under existing prices that are offered . . . it's not evident that existing homes will have an attractive return." These contrasting opinions suggest that although the building blocks for financial motivation may already be in place, they are insufficient to cause household adoption to reach a tipping point (Faiers and Neame 2006). This disagreement may indicate a place where policy change could be particularly effective; a larger incentive could effectively increase this motivation (Bauner and Crago 2015).

All three motivation categories contained a factor that the expert panel identified by consensus as being relevant to the context in Santiago, Chile. However, none of these were ranked as very important (score of 5) to the decision to install a household solar system. This may in part be attributable to the scale of the motivation in the Santiago context. For example, if there were additional subsidies, or if more attractive rates for excess energy sold back to the grid were available from the government, the financial motivation would be more compelling. Similarly, in contexts with less-reliable grids, the energy reliability motivation would likely be stronger, and in contexts with less trust in the centralized government, the energy independence motivation would likely be stronger. It is less evident when environmental motivations would be stronger. Perhaps this would be observed in communities particularly impacted by or otherwise knowledgeable about climate change. Researchers have investigated the topic of householders' attitudes, of behavior surrounding investment in climate change–mitigating technologies (e.g., Bird and Sumner 2011), and of their associated willingness to pay for these technologies (Lee and Cameron 2008). The field's body of knowledge as well as Chilean policy development could benefit from similar investigations within the Chilean context.

Barriers

Arrayed between the triumvirate of motivations and the choice to invest in PV are a set of barriers. Like the motivations, these barriers are places where, in a particular context, policy change can make particular energy technologies more attractive. As discussed in the literature review, the academic literature suggests that there are financial, knowledge, technical, and institutional reasons that an energy technology might not be selected. As hypothesized in Fig. 1, these barriers moderate household decisions to invest in solar PV. Discussed next are the particular barriers identified by the expert panel for the Chilean context. This is followed by a discussion of those barriers that were not reached by consensus. As a relative indication of the importance of each category, a normalized factor score is listed that includes all factors within each category that were identified by consensus.

Financial Barriers (Normalized Category Score: 4.3)

The highest normalized score observed in this study belonged to the category of factors that treat financial barriers. One of these factors—purchase-price variation [20, 4.0, 0.0]—scored 4.0. Another one—initial investment [1, 4.5, 1.0]—scored 4.5. It may be encouraging that these factors were seen as the highest barrier (in the Chilean context). Indeed, the financial barriers may, given proper resources, be addressed by policy. One expert mentioned that with regards to the initial investment of capital costs [1, 4.5, 1.0], there are "financial pathways with low interest rates that can reduce this barrier." For purchase-price variation of different PV technologies [20, 4.0, 0.0] ("there are big differences between prices, and the user doesn't have sufficient information to discriminate between them"), this barrier might be removed with an informational tool about current cost ranges. In terms of price variation, however, one expert stated, "the price isn't everything, the service is fundamental when one is buying a product" [20, 4.0, 0.0].

Incomplete Knowledge Barriers (Normalized Category Score: 3.8)

Of the six factors that had to do with incomplete knowledge, the experts were all in consensus. These factors ranged in importance from 4.5 (difficulty of finding comparable cost information [6, 4.5, 1.0]) to 3.0 (knowledge regarding system maintenance [8, 3.0, 1.0], and lack of education or training events [19, 3.0, 0.25]). The highest-ranked barrier in this category (difficulty of finding comparable cost information [6, 4.5, 1.0]) was related to one in the financial barrier category (price variation [20, 4.0, 0]). These two barriers together mean that costs not only vary widely but are also difficult to compare. A related barrier treats the lack of technical knowledge about household solar systems and how to have one installed [3, 4.0, 0.5]: "It's indispensable to know about solar photovoltaics; otherwise, how would you decide?" In addition, although "there is evidence of a number of successful installations, the problem grows because information always circulates between the same market participants and never gets to the final client." In contrast, the experts felt knowledge gaps regarding system maintenance [8, 3.0, 1.0] were less important: "The maintenance of photovoltaic systems is minimal."

Of all the factors in this category, the one generating the most discussion was that describing educational efforts [19, 3.0, 0.25]. Experts mentioned that it is "fundamental to educate" and that there are "free tools that help to model solar voltaic systems, but they have been little promoted." However, another expert felt this was an issue of demand as well as supply: "There have been many initiatives and workshops that have low attendance . . . I attribute this to the lack of dissemination." In addition, these educational opportunities are limited by geography: "Outside of Santiago, there is not much knowledge of this idea [of household PV]."

Institutional Barriers (Normalized Category Score: 3.8)

Five factors were categorized as institutional barriers. These barriers include the existence of photovoltaic companies for both installation [9, 4.0, 0.5], energy independence [26, 3.9, 1.5], postsale maintenance services [15, 3.5, 1.0], maturity of the market [10, 4.0, 0.5], and the existing legal framework [14, 4.0, 1.0]. Only three of these five barriers were identified by consensus, suggesting considerable disagreement about the importance of institutional factors. For example, Chilean Ley 20.571 is a net-billing framework that defines the generation, sale, and distribution of excess energy produced by the user (Ley 20.571 2014). Although experts agreed that the public could find information about the benefits of this law [14, 4.0, 1.0], there was considerable disagreement about the barrier regarding the complexity of this law for users [13, 4.0, 1.25 (no consensus)]. One expert said, "They should simplify the process, it's very cumbersome and costly." Another said, "The regulation is simple and currently it is being changed to better facilitate the processing and related time." This factor is discussed further later, along with other factors that were not identified by consensus.

Beyond the regulatory framework, the experts also identified organizational challenges. Several experts were concerned that "people [didn't] know how to find or evaluate them [solar companies]." "More than anything," these experts stated, "it's a problem with the dissemination of information." One expert mentioned that "the primary problem is the lack of knowledge of the public. Because of this the market can't mature." In contrast, another commented, "If there really are providers of systems for households, the offerings are opaque, with a wide range of prices and margins that reduce the possibility for residential clients." In sum, the high normalized score and high level of disagreement regarding various aspects indicate that institutional barriers remain a considerable challenge (second only to financial barriers) to residential PV adoption in Chile.

Technical Barriers (Normalized Category Score: 2.8)

Although the technical factors were the most numerous, they collectively received the lowest normalized category score. This is primarily attributable to two factors (pollution-reducing panel performance [4, 2.0, 0.5], and use of non-sun-tracking systems [18, 2.0, 1.0]) that experts felt were relatively unimportant. Still, although these factors were identified by consensus, there was some disagreement reflected in the interquartile ranges. For example, regarding the potential for Santiago's air pollution to make a film on solar panels and reduce their performance [4, 2.0, 0.5], one expert suggested simply "implementing a system of periodic cleaning" to eliminate the problem. However, another expert reported: "I have real information from different parts of the metropolitan region, and the efficiency is strongly impacted." As evidence, this expert referenced a recent study by Caceres et al. (2014) that investigated the effects of dust and air pollution on solar-cell efficiency in Santiago.

Regarding the use of non-sun-tracking systems [18, 2.0, 1.0], an expert noted that "with solar tracking, the cost increases . . . It's more convenient to install stationary systems." The experts stated that concerns regarding the shading of panels by tall buildings in Santiago's urban environment [16, 3.0, 0.5] are valid but "the examples are few." Roof damage from the mounting of solar panels [12, 3.0, 0.5] could be avoided "if you follow the procedures and work with adequate materials." These factors were accordingly rated as only somewhat important. Finally, the aesthetics of household solar systems [24, 3.0, 1.0] were included in the technical category because their appearance is limited by technical requirements. It is not presently technically feasible, for example, to change the aesthetics by making solar panels appear to be traditional roofing shingles. This factor was felt to be somewhat important. One expert said "I'd say that not an insignificant percentage [of people] disapprove" of panel appearance.

Factors That Did Not Reach Consensus

Experts failed to reach a consensus on five of the factors—lack of knowledgeable companies [9, 4.0, 0.5], energy independence [26, 3.0, 1.5], complexity of Law 25.571 (net-billing) [13, 3.5, 1.25], energy supply and demand timing [11, 4.0, 0.5], and uncertain ROI [21, 4.0, 0.25]. The lack of consensus suggests these are places where future research should be focused to better understand the impact of these factors and how they may be managed through policy. These factors are discussed in subsequent subsections.

Knowledgeable Companies [9, 4.0, 0.5]

This factor represented the potential lack of knowledgeable companies that could provide PV design, installation, or maintenance. The experts found that "good companies offering these services already exist." Some experts were concerned about "a big problem with professionalism, and an important explosion of installers who don't meet any standards of safety or quality." Two experts identified "a problem of information diffusion" regarding the companies that do exist. Both of these experts reported that, in the Santiago context, a lack of companies is not an important factor. Still, despite these two low scores the (nonconsensus) median score for this factor was a 4.0, indicating that most of the expert panel felt there was indeed a shortage of knowledgeable local companies.

Overall, the scores and comments indicate that the nonconsensus is attributable to disagreement between (1) experts who think there is an actual shortage of knowledgeable companies, and (2) experts who think there is a sufficient number of companies, but problems regarding how the public would go about identifying and evaluating those companies. A potential policy solution to this issue would be a government-maintained list of registered PV companies. This would both aid the public in finding reputable firms and enable a reliable count of firms in the market.

Energy Independence [26, 3.0, 1.5]

This factor represented the potential desire of homeowners to generate electricity themselves rather than drawing it from the grid. Some experts related this factor to grid reliability (excellent in Santiago), but others related it to managing uncertainty in future electricity cost. This difference explains the differences in expert opinion on the importance of energy autonomy to households. For example, one expert scored this factor a 1 (not important), stating, "The energy grid in Santiago is reliable, and [independence from the grid] is not an additional motivation to invest." Agreeing with this point, another expert remarked, "I think [that households] use PV as a complementary alternative, not as a substitute [for energy from the grid]."

In contrast, another expert (individual score of 4) focused on the benefit to households regarding variations in electricity tariffs: "It is important from the standpoint that [households] can reduce their dependence on the variation of the tariffs associated with the energy purchased from the distributer, which helps them plan operational costs over the long-term." Regardless, one expert stated that achieving independence from the electrical grid "is a common question from our clients." Because the grid is very reliable in Santiago, this issue is not, in this particular context, a driver for the use of household solar systems. However, and as is common worldwide, the existing tariff schemes (discussed later) do not address uncertainties of future electricity costs. As such, homeowners who are concerned about this issue are more inclined to construct their own generation capacity.

Law 25.571: Complexity [13, 3.5, 1.25]

This factor represented the complexity of the Chilean net-metering regulation. There are two subsets of opinion regarding this factor. In a quote representative of one of these subgroups, an expert stated that Law 25.571 "is a bit confusing and should interact with the distribution company who is the interested party." However, the majority of experts who commented indicated that the regulatory net-billing framework is already in the process of being simplified. One expert stated that "the SEC [Electricity and Gas Utility of Santiago] is modifying the regulation with something that is hoped will resolve a lot of this problem." Another stated that "the regulatory framework is already simple, yet they [SEC] are modifying it to streamline the connection procedure and the time associated." In addition to this clearly important work regarding regulatory simplification, this issue suggests the importance of knowledgeable organizations that could help interpret the laws for homeowners.

Energy Supply and Demand Timing [11, 4.0, 0.5] and Uncertain ROI [21, 4.0, 0.25]

This subsection presents a discussion of these two factors together (timing of when PV generates electricity versus when people use the most electricity, and uncertainty regarding the return on a household's investment in PV). This seems appropriate because of the major difference in opinion regarding the impact of solar supply and demand patterns on costs to households, and the combined effects this could have on ROI. One expert said, "In the energy-supply tariffs that are differential, this [issues with variable energy generation] is not relevant because the value of energy purchased and sold is the same. An exception is the case in tariff BT1." This expert's insight points to an important caveat of the existing Chilean net-billing (Ley 20.571) scheme; it relates to the balance in energy supply and buy-back rates. Most households use the energy tariff BT1, which provides a fixed rate for energy consumption for installations under 10 kW in capacity (instantaneous draw) (SECb 2016). Residential users with this tariff only measure energy consumption. Therefore, capacity payments are included indirectly by adding a certain amount to the energy (kWh) price. The capacity payment included in the energy rate for BT1 covers the overall capacity requirement of the demand, yet the 20.571 net-billing law only buys back energy at the lower base energy rate. Thus, in many cases, the price of energy purchased in the case of BT1 would not be equivalent to the price of energy sold back to the grid–an important constraint to ROI. As a result, the current energy-supply tariff schemes in Chile, whether combined (BT1: total energy used and instantaneously drawn are combined in the cost) or differential (tariff schemes BT2—BT4.3: energy and draw are treated separately), could adversely affect the net benefits gained by the homeowner.

The literature indicates that a major barrier to household solar PV adoption is uncertainty of ROI in general, and payoff timeline in particular (Rai et al. 2016; Rai and McAndrews 2012). Indeed, most of the experts indicated this barrier [21, 4.0, 0.25] was important. One expert said, "Economic performance is always the most important." Experts could not reach a consensus, however, not because of a high IQR (it received a low IQR of 0.25) but because of the score range (less than or equal to 3) requirement. Indeed, all the experts rated this factor as either a 4 or 5, except one expert, who rated it a 2. That expert called attention to the coupled influence of energy supply and demand timing, electricity tariffs, and ROI:

> ROI is only one of the various relevant factors. In the majority of cases, there will be some sort of ROI; however, this varies depending on the development of energy production and consumption schemes (differential versus fixed rate tariffs). In the case of BT1, on the consumption profile and the percentage of surplus.

Another expert rated this factor as important (individual score of 4) but agreed that the importance of ROI is variable and dependent on context, mentioning that "given the prices that are offered, it is not evident that existing houses will have an attractive economic return. Those houses that might are new houses."

In summary, these contested factors highlight potentially critical aspects about Santiago's adoption climate. They show a lack of agreement on factors such as ROI, which researchers expected to be unanimously rated with high importance. Additionally, these barriers identify issues with the identification or existence of installation companies to adequately serve interested households. Finally, they highlight a feature of the existing regulatory framework that may dissuade homeowners from investing in PV, either because of real monetary impact or because of increased uncertainty regarding the potential ROI because of regulatory complexity. Although experts in this study did not reach a consensus on these five factors, their discussions regarding them point to particularly rich topics for future research.

Conclusions and Policy Recommendations

In Fig. 3, the motivations and barriers about which experts reached a consensus are used to detail an analytic framework for domestic solar PV adoption particular to the context of Santiago, Chile. A contextual adaption of the framework proposed in Fig. 1, this figure displays the interconnection between motivations and barriers, where the strength of motivation categories (solid circles) and barriers (grey circles) are sized based on each category's relative normalized importance score, as indicated by the experts.

The normalized scores (and scaled circles) in Fig. 3 demonstrate that the strength of barriers exceeds that of motivations for households to invest in a PV technology. This aligns with what has been observed in Santiago, namely, a negligible uptake of PV energy technologies in households. In light of these motivations, barriers, and their inferred interconnection, the literature points to specific solutions to encourage adoption in the Santiago and Chilean context. For example, a coupled motivation-barrier interaction exists between the need for simple regulation [13, 3.5, 1.25] and financially attractive subsidies [2, 4.0, 0.25] that minimize initial upfront costs [2, 4.0, 1.0]. A policy-based solution is to offer leasing and buying models (an offer that would be particularly attractive to nonhomeowners) (Davidson et al. 2015; Rai and Sigrin 2013), or innovating nontraditional approaches such as PV system giveaways (Zhang et al. 2015). Benefits from these policies could be further leveraged by streamlining household access to concise information regarding available price [20, 4.0, 0.0], technology options [3, 4.0, 0.5] for PV systems (Margolis and Zuboy 2006; Rai et al. 2016), and existing knowledgeable firms [9, 4.0, no consensus].

In addition, it could be beneficial to develop and advertise communication platforms or workshops to educate users [19, 3.0, 0.25] (Rai and Robinson 2013) and increase the visibility of successful projects [17, 4.0, 0.25]. Examples of this latter point could include demonstration sites with visually conspicuous placement of solar panels (Richter 2014). Lastly, a powerful system leverage point

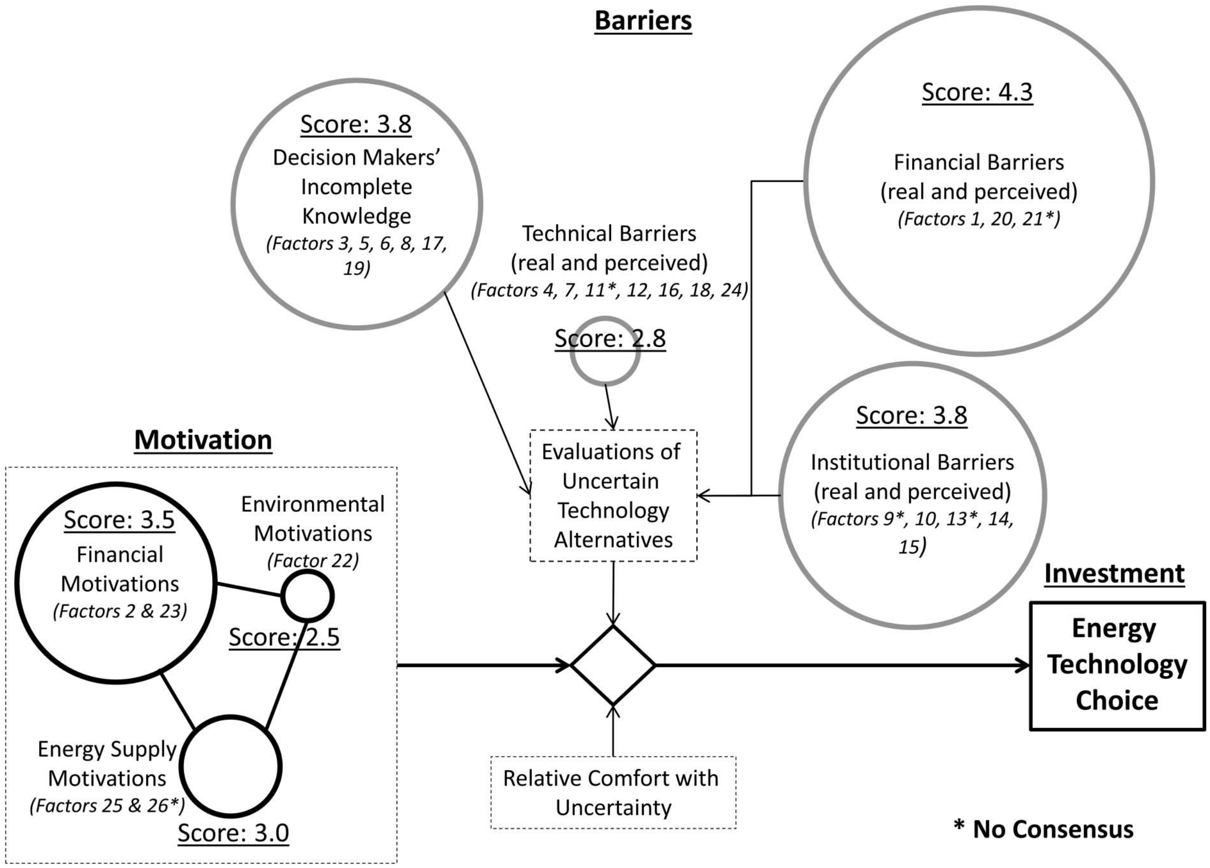

Fig. 3. Adoption framework for Chile; motivations (solid circles) and barriers (gray circles) are sized based on the normalized score of importance indicated by the experts (underlined); scale exaggerated for visual clarity

is the revising of the Chilean residential electricity tariff scheme (BT1) to ensure simple and transparent electricity rates [14, 4.0, 1.0]. In addition, the use of a differential rate that better balances electricity purchase and sale rates for households could contribute to households' financial motivation to install PV.

Overall, domestic PV usage in Santiago, Chile, presents a compelling urban case study of a theoretically ideal consumer base that has not yet achieved significant uptake of household PV technology. The findings align with most solar literature, which points to household adoption being inhibited by high upfront costs and uncertainty in financial returns as barriers. Building on this existing work, the results of this study contribute to more recent literature that highlights the complex and beguiling interplay among social and institutional factors that influence a household's decision to invest in solar PV technology. In doing so, this study can help shape ongoing research and practice that seeks to improve solar technology pricing and payment schemes to create a tipping point for solar energy transition. Moreover, it provides further impetus for future investigations in solar PV technology construction, engineering and management that seek to gain a deeper understanding of the complex, systems-based interactions among the social, technical, financial, and institutional factors influencing household solar PV adoption.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data sharing policy can be found here: http://ascelibrary.org/doi/10.1061/%28ASCE%29CO.1943-7862.0001263.

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References

Baron, R. M., and Kenny, D. A. (1986). "The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations." *J. Personality Soc. Psychol.*, 51(6), 1173–1182.

Bauner, C., and Crago, C. L. (2015). "Adoption of residential solar power under uncertainty: Implications for renewable energy incentives." *Energy Policy*, 86, 27–35.

Beck, F., and Martinot, E. (2012). "Renewable energy policy and barriers." *Encyclopedia Energy*, 5, 365–383.

Bird, L., and Sumner, J. (2011). "Consumer attitudes about renewable energy. Trends and regional differences." National Renewable Energy Laboratory, Golden, CO.

Bollinger, B., and Gillingham, K. (2012). "Peer effects in the diffusion of solar photovoltaic panels." *Marketing Sci.*, 31(6), 900–912.

Cáceres, G., Nasirov, S., Zhang, H., and Araya-Letelier, G. (2014). "Residential solar PV planning in Santiago, Chile: Incorporating the PM10 parameter." *Sustainability*, 7(1), 422–440.

Chilean Ministry of Energy. (2012). "Energy for the future: National energy strategy 2012–2030." Santiago, Chile.

Chilean Ministry of Energy. (2014). “Agenda de Energía: Un Desafío País, Progreso Para Todos.” Santiago, Chile.

Davidson, C., Steinberg, D., and Margolis, R. (2015). “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(2), 024006.

Escobar, R. A., Cortés, C., Pino, A., Pereira, E. B., Martins, F. R., and Cardemil, J. M. (2014). “Solar energy resource assessment in Chile: Satellite estimation and ground station measurements.” *Renewable Energy*, 71, 324–332.

Faiers, A., and Neame, C. (2006). “Consumer attitudes towards domestic solar power systems.” *Energy Policy*, 34(14), 1797–1806.

Grágeda, M., Escudero, M., Alavia, W., Ushak, S., and Fthenakis, V. (2016). “Review and multi-criteria assessment of solar energy projects in Chile.” *Renewable Sustainable Energy Rev.*, 59, 583–596.

Graziano, M., and Gillingham, K. (2015). “Spatial patterns of solar photovoltaic system adoption: The influence of neighbors and the built environment.” *J. Econ. Geogr.*, 15(4), 815–839.

Hallowell, M. R., and Gambatese, J. A. (2010). “Qualitative research: Application of the Delphi method to CEM research.” *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000137, 99–107.

Helmer-Hirshberg, O. (1967). “Systematic use of expert opinions.” RAND Corporation, Santa Monica, CA.

IRENA (International Renewable Energy Agency). (2015). “Renewable energy policy brief: Chile.” Abu Dhabi, United Arab Emirates.

Kaminsky, J. A. (2016). “Cultured construction: Global evidence of the impact of national values on renewable electricity infrastructure choice.” *Environ. Sci. Technol.*, 50(4), 2108–2116.

Lee, J. J., and Cameron, T. A. (2008). “Popular support for climate change mitigation: Evidence from a general population mail survey.” *Environ. Resour. Econ.*, 41(2), 223–248.

Ley 20.571. (2014). “Regula el pago de las tarifas eléctricas de las generadoras residenciales.” ⟨http://www.minenergia.cl/ley20571/wp-content/uploads/2015/03/Ley20.571.pdf⟩ (Jun. 4, 2016).

Linstone, H. A., and Turoff, M. (2002). *The Delphi method: Techniques and applications*, Addison-Wesley, Boston, 53.

Margolis, R., and Zuboy, J. (2006). *Nontechnical barriers to solar energy use: Review of recent literature*, National Renewable Energy Laboratory, Golden, CO.

Popp, D., Hascic, I., and Medhi, N. (2011). “Technology and the diffusion of renewable energy.” *Energy Econ.*, 33(4), 648–662.

Rai, V., and McAndrews, K. (2012). “Decision-making and behavior change in residential adopters of solar PV.” *Proc., World Renewable Energy Forum*, American Solar Energy Society, Boulder, CO.

Rai, V., Reeves, D. C., and Margolis, R. (2016). “Overcoming barriers and uncertainties in the adoption of residential solar PV.” *Renewable Energy*, 89, 498–505.

Rai, V., and Robinson, S. A. (2013). “Effective information channels for reducing costs of environmentally-friendly technologies: evidence from residential PV markets.” *Environ. Res. Lett.*, 8(1), 014044.

Rai, V., and Sigrin, B. (2013). “Diffusion of environmentally-friendly energy technologies: Buy versus lease differences in residential PV markets.” *Environ. Res. Lett.*, 8(1), 014022.

Raskin, M. S. (1994). “The Delphi study in field instruction revisited: Expert consensus on issues and research priorities.” *J. Soc. Work. Educ.*, 30(1), 75–89.

Richter, L. (2014). “Social effects in the diffusion of solar photovoltaic technology in the UK.” Univ. of Cambridge, Cambridge, U.K.

Rogers, E. M. (1983). *Diffusion of innovations*, 3rd Ed., Free, New York.

SECa. (2016). “Summary of Registered Residential Solar Systems in Santiago, Chile.” *Información No. AU004T0001070*, Hamburg, Germany.

SECb. (2016). “ Tarifas Electricas. Chile.” ⟨http://www.sec.cl/portal/page?_pageid=33,3417541,33_3421567&dad=portal&schema=PORTAL⟩ (Aug. 24, 2016).

Shakouri, M., Lee, H. W., and Kim, Y.-W. (2017). “A probabilistic portfolio-based model for financial valuation of community solar.” *Appl. Energy*, 191, 709–726.

Sovacool, B. K. (2009). “Rejecting renewables: The socio-technical impediments to renewable electricity in the United States.” *Energy Policy*, 37(11), 4500–4513.

Sovacool, B. K. (2014). “What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda.” *Energy Res. Soc. Sci.*, 1, 1–29.

Thiam, D. R. (2011). “An energy pricing scheme for the diffusion of decentralized renewable technology investment in developing countries.” *Energy Policy*, 39(7), 4284–4297.

von der Gracht, H. A. (2012). “Consensus measurement in Delphi studies.” *Technol. Forecasting Soc. Change*, 79(8), 1525–1536.

Watts, D., Valdés, M. F., Jara, D., and Watson, A. (2015). “Potential residential PV development in Chile: The effect of net metering and net billing schemes for grid-connected PV systems.” *Renewable Sustainable Energy Rev.*, 41, 1037–1051.

Yuventi, J., Levitt, R. E., and Robertson, H. (2013). “Organizational barriers to productivity and innovation in large-scale, U.S.-based photovoltaic system construction projects.” *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000767, 06013003.

Zhang, H., Vorobeychik, Y., Letchford, J., and Lakkaraju, K. (2015). “Data-driven agent-based modeling, with application to rooftop solar adoption.” *Proc., 2015 Int. Conf. on Autonomous Agents and Multiagent Systems*, International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 513–521.

Zhang, Y., Song, J., and Hamori, S. (2011). “Impact of subsidy policies on diffusion of photovoltaic power generation.” *Energy Policy*, 39(4), 1958–1964.