Project Title: Towards an Emergent Model of Technology Adoption for Accelerating the Diffusion of Residential Solar PV

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PUBLICATIONS AND OUTREACH

Scholarly and Trade Presentations (6)

1. Towards an Emergent Model of Technology Adoption for Accelerating the Diffusion of Residential Solar PV. Department of Energy, **DOE Decision Science and Market Transformation Pathways Workshop**, Washington DC, 12/15.
2. Predictive Modeling of Consumer Energy Technology Adoption. **Georgia Tech**, 11/15.
3. Energy Games: Gamification for Decision-making and Behavior Change in Solar Adoption. ***UT Energy Symposium***, UT Austin, Texas, September 2015.
4. Drivers of Residential PV Adoption: Toward Predictive Modeling and Understanding Infrastructure Implications. ***Electric Reliability Council Of Texas (ERCOT)***, Workshop on Scenario Development for Long Term System Assessment, Austin, Texas, July 2015.
5. Connecting the Dots Between Theory, Simulations, and Experiments. ***NYSERDA/American Academy of Sciences***, Workshop on Applying Behavioral Strategies to Energy Decisions and Behaviors, White Plains, New York, June 2014.
6. Predicting Patterns of Energy Technology Adoption: An Agent-based Approach. ***University of Wisconsin-Madison***, April 2014.

Conference Papers (6)

1. Beck, A., Lakkaraju, K., and Rai, V. Information Salience and Behavior Change in Solar: Three Experiments Comparing Passive and Active Information Delivery, Baltimore, MD, October 2016.
2. Reeves, D. C. and Rai, V. Effective Information Seeding Strategies to Accelerate Solar Adoption. *Behavior, Energy and Climate Change Conference*, Sacramento, CA, October 2015.
3. Robinson, S. A. and Rai, V. Role of Information and Incentives in Technology Adoption: Household-level Predictive Modeling. *Behavior, Energy and Climate Change Conference*, Washington D.C., December 2014.
4. Rai, V. and Beck, A. Adoption of Energy Efficiency Measures and Rooftop Solar: An Online Gamification Study. *Behavior, Energy and Climate Change Conference*, Washington D.C., December 2014.
5. Stringer, M. and Rai, V. Geography and Growth: Clustering in the Diffusion of Innovations. *37th IAEE/USAEE Conference*, New York City, USA, June 2014.
6. The New Science of Soft Costs: Towards an Emergent Model of Technology Adoption for Accelerating the Diffusion of Residential Solar PV. *Department of Energy Solar Summit*, Anaheim, CA, May 2014.

Journal Papers (5)

1. Rai, V. and Beck. A. L. (2016) Serious games in breaking informational barriers in solar energy. *Under Review.* Preprint available at: http://ssrn.com/abstract=2816852
2. Rai, V., & Henry, A. D. (2016). Agent-based modelling of consumer energy choices. *Nature Climate Change*, DOI: 10.1038/NCLIMATE2967.
3. Rai, V., & Beck, A. L. (2015). Public perceptions and information gaps in solar energy in Texas. *Environmental Research Letters*, *10*(7), 074011.
4. Robinson, S. A., & Rai, V. (2015). Determinants of spatio-temporal patterns of energy technology adoption: An agent-based modeling approach. *Applied Energy*, *151*, 273-284.
5. Rai, V., & Robinson, S. A. (2015). Agent-based modeling of energy technology adoption: empirical integration of social, behavioral, economic, and environmental factors. *Environmental Modelling & Software*, *70*, 163-177.

Towards an Emergent Model of Technology Adoption for Accelerating the Diffusion of Residential Solar PV

PI: Varun Rai, The University of Texas at Austin

I. MOTIVATION AND RESEARCH FOCUS

This project sought to enable electric utilities in Texas to accelerate diffusion of residential solar photovoltaic (PV) by systematically identifying and targeting existing barriers to PV adoption. A core goal of the project was to develop an integrated research framework that combines survey research, econometric modeling, financial modeling, and implementation and evaluation of pilot projects to study the PV diffusion system (Section III.A). A theoretically-based, holistic dataset on PV-owning and non-adopter households across Texas was developed, with detailed technical, financial, demographic, social, and behavioral data across spatial (neighborhood, zip-code, county, and state level) and temporal (2004-2015) scales. This project considered PV diffusion as an emergent system, with attention to the interactions between the constituent parts of the PV socio-technical system including: economics of individual decision-making; peer and social influences; behavioral responses; and information and transaction costs. We also conducted two pilot projects (Sections III.B and III.C), which have yielded new insights into behavioral and informational aspects of PV adoption. Finally, this data-driven and computationally-focused project has produced robust and generalizable results that will provide deeper insights into the technology-diffusion process that will be applicable for the design of utility programs for other technologies such as home-energy management systems and plug-in electric vehicles.

When we started this project in 2013 there was little systematic research on characterizing the decision-making process of households interested in adopting PV. This project was designed to fill that research gap by analyzing the PV adoption process from the consumers' decision-making perspective and with the objective to systematically identifying and addressing the barriers that consumers face in the adoption of PV. The two key components of that decision-making process are consumers' evaluation of: (i) uncertainties and non-monetary costs associated with the technology and (ii) the direct monetary cost-benefit. This project used an integrated approach to study both the non-monetary and the monetary components of the consumer decision-making process.

II. RESEARCH TEAM

The PI, **Dr. Varun Rai**, is an assistant professor at the LBJ School of Public Affairs and in the Mechanical Engineering Department at The University of Texas at Austin (UT), where he directs the Energy Systems Transformation Research Group. The PI's research is devoted to the systematic study of innovation and diffusion of energy technologies, an area that he studies using a combination of different research methods. The emphasis of his research is on interdisciplinary and integrative research in engineering and policy to ensure that the insights from his policy research are rooted in the underlying technical realties.

In addition to the PI, two other senior personnel added critical expertise to the team: Dr. J. Eric Bickel and Dr. Jay Zarnikau. **Dr. Bickel** is an associate professor in the Operations Research / Industrial Engineering Group (Department of Mechanical Engineering) at The University of Texas at Austin. His research interests include the theory and practice of decision analysis and its application in the energy and climate-change arenas. His research has addressed the use of climate engineering to combat climate change, the modeling of probabilistic dependence, value of information, scoring rules, calibration, and risk preference. Dr. Bickel's research established expertise in decision analysis and value of information successfully bridges the gap between traditional and behavioral economics, which was a key part of this project.

Dr. Zarnikau is an adjunct professor of Public Policy and Statistics at The University of Texas at Austin. His research centers on energy pricing, electricity resource planning, renewable energy, energy efficiency, and the application of modeling techniques to problems in resource economics. As the president of Frontier Associates, an energy a consulting firm, Dr. Zarnikau provides consulting assistance to utilities, retail electric providers, and energy consumers in the design and evaluation of energy efficiency programs, retail market strategies, electricity pricing, demand forecasting, and energy policy. Dr. Zarnikau provided our research team with essential linkages to the business side of solar PV and electricity markets.

III. COMPLETED WORK AND MAJOR ACCOMPLISHMENTS

A. Integrated Modeling of Residential PV Adoption

Three novel analysis methods were developed, tested, used to model PV adoption, and were validated against real-world of residential PV adoption in Austin, Texas during 2004 – 2015. (1) First, a social network model was developed to model social interactions and peer effects among residential customers. This social network model is described in more detail below. (2) The second method enables mapping/extrapolation of individual-level attributes (such as “attitude” toward solar) across the entire population at the individual level using measurements for only a small sub-sample of the population; this method is based on using kriging spatial regression. Details of this method are available in Rai & Robinson (2015), which was developed as part of this SEEDS project. (3) The third method is an integrated agent-based modeling (ABM) framework to model the spatial-temporal characteristics of the PV adoption process at the household-level resolution. Highlights of the integrated model are provided below, with additional details presented in Rai & Robinson (2015) and Robinson & Rai (2015).

A.1 Social Network Model

We have developed a social network model based on empirical patterns of PV adoption and additional theoretical insights (such as homophily and complexity of social networks). In particular, we used a small-world network where λ connections were random and 1 - λ connections were locals. Locals were defined geographically by a radius parameter (r=2000 ft) around each household. The radius parameter *r*, in turn, was determined by calculating a relevant distance from the empirical data: we looked at multiple distance bands, and calculated the spatial autocorrelation between adopter locations for each. In accordance with the known strong peer-effects in residential solar adoption, r was chosen as the distance at which PV adopter clusters are the strongest. Because these clusters arise through interaction within the neighborhood, the use of empirical clustering to determine the best distance by which to define the locals set arises from an observed pattern and prior empirical work. Further, in line with existing literature we find that small-world social networks where locals are based on geography alone, even when the relevant distance is derived from empirical patterns, generated very high degree distributions. To achieve more realistic degree distributions, we further refined these connections based on home-value similarity. Economic similarity (calculated as the squared difference in home values) was used to further refine the locals set, whereby only 5% of the geographic locals set was retained in the final locals set used in the simulations. Thus, in our social network model the majority of an agent's connections are geographic and economic neighbors. That is, a household is more likely to be connected with (and hence interact with) other households that are nearby and have similar wealth characteristics. **Figure 1** shows a portion of the resulting network. Importantly, this is an automated method that can be applied to any study area and for any technology influenced by social interaction effects. Further details of this approach are provided in Rai & Robinson (2015).

A.2 Integrated Agent-based Modeling Framework

We have successfully built and validated an integrated modeling framework to analyze the residential solar adoption process (**Figure 2**). In particular, using a uniquely rich and comprehensive dataset between 2004-2015, we have built an agent-based model (ABM) of the adoption of residential solar photovoltaic (PV) systems in the City of Austin (Texas, USA), which has a population of approximately 900,000. In addition to an empirically driven agent-interaction model and a theoretically-driven behavioral model, we also account in great detail for the physical environment (irradiation, tree cover, home size) and economic features (prices, subsidies, wealth) that impact agent behavior, again using empirical data.

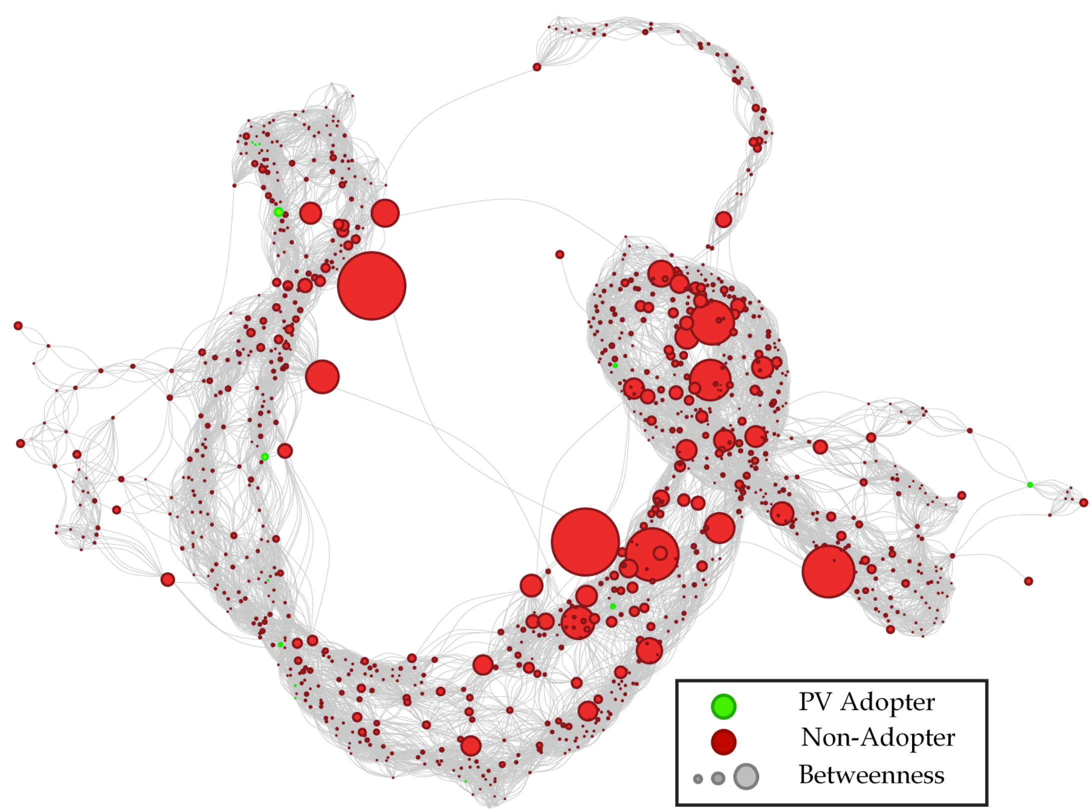

Figure 1: Representative portion of the small world network used in the solar ABM. The shown network is only for the N = 1054 agents in a single zip code in the study area. Nodes represent individual household agents, and edges represent agents connected in the network. While the underlying network uses actual geographical location of the agents to define the locals set (see text), note that for a convenient visualization, length of the edges do not represent actual geographical

distance. Green dots are solar adopters (N = 15) in the zip code used for the visualization, red dots are non-adopters, and size of the dots reflects the betweenness centrality of each node.

The main achievements of the modeling work completed in this project include: (i) development of a theoretically and empirically grounded integrated model for consumer technology adoption, applied to residential solar, (ii) highly granular description of the system, including behavioral, social, and physical-economic environmental aspects at the household level, (iii) development of new techniques to achieve a population-wide, household-level empirical initialization, and (iv) development and application of multiple (temporal, spatial, and demographic) external validation metrics.

Additional details are available in two published papers based on the work in this project: Rai & Robinson (2015), and Robinson & Rai (2015). In these papers we present a detailed step-by-step construction of the different components of the ABM, the process of initializing the model, and setting up of the model parameters and variables in accordance with the theoretical and empirical underpinnings of the system. In the papers, we also present methods for temporal and spatial validation of the model along with the fitting and validation results. The emphasis is to provide a greater level of detail in the construction of the behavioral model, data integration, and initialization procedures, which are critical to making the model reproducible.

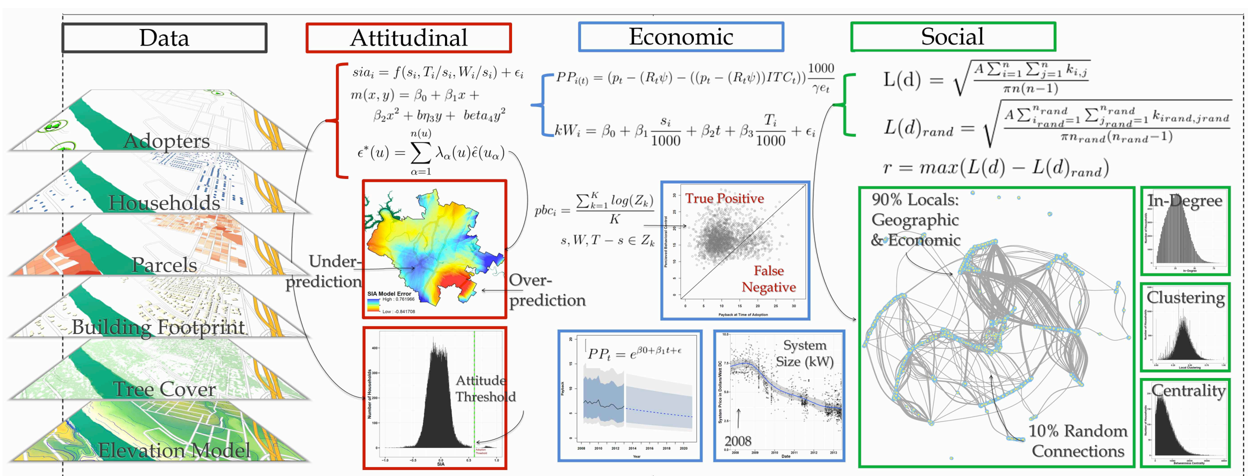

Figure 2: The developed modeling framework. The emphasis was to create a predictive modeling framework that is extremely rich in incorporating all relevant spatial, technical, behavioral, economic, and social aspects to enable the representation and study of the residential solar adoption process.

A.3 Overall Summary of Modeling Work Completed in this Project

Overall, we have developed a comprehensive approach for the integration of granular and overlapping data-streams to ground ABM of residential solar adoption empirically, while building upon theoretical underpinnings. Specifically, our modeling framework is based upon an empirical, geographic information system (GIS)-integrated agent-based model of solar adoption to explore the importance of using empirical household-level data and of incorporating economic *and* social and behavioral factors on model outcomes. In order to address concerns regarding representativeness and over-fitting in ABM generally, we have developed and applied to the integrated agent-based model a multidimensional external validation process. This is important because only by thoroughly grounding the model components in real-word data and through rigorous validation can ABM generate relevant policy insights, predictions, and emergent properties beyond the reach of conventional models (Rai & Henry, 2016).

Furthermore, we find it necessary to use multiple validation checks in assessing the performance of the different models considered. This is especially important when modeling systems with multi-layered environmental and social interactions that impact agent behavior, as in the case of solar adoption. In general, more granular data and less reliance on random distributions for describing the system increases model fit and validity. The important point here is that the validity of a model critically depends upon the underlying data and the level of abstraction: the same model may perform well for highly-aggregated outcomes (i.e., scale of adoption), while doing poorly in describing the structural aspects (e.g., spatial, demographic, etc.) of the system at lower levels of abstraction.

B. Pilot 1: Gamified Information System ("*Energy Games")*

The adoption of solar energy and energy conservation – widely assumed to be pivotal to a new energy transformation – has been hindered by persistent information gaps. Providing information alone is not sufficient for bridging these gaps or motivating behavior change. In this pilot we explored a different approach – known as "serious games" – in which participants actively engage with actionable information presented through a game interface, in this case a trivia-style game. Using a randomized control trial (RCT) design we assessed the potential of serious games (i.e., games with a primary purpose other than entertainment) to influence attitudes, norms, and the perception of control, which are known to impact intentions and behavior, toward solar energy and energy conservation in residential energy customers.

Working in collaboration with two electric utilities – AEP Texas North and AEP Texas Central, in this pilot we delivered an electronic information campaign to over 550 solar non-adopters in several parts of Texas. The main impetus for us to work with these two utilities was to develop a controlled, information and data-collection campaign. Potential participants were randomly selected from an address list for residential meters in the AEP Texas North and AEP Texas Central territories. While a list of addresses for every residential meter was available, no names, emails, or additional demographic data was available. Thus we used a direct marketing campaign – in two waves – with postcards advertising the research study. Due to the study's focus on solar adoption, the address list was first filtered for zip codes in Corpus Christi (AEP Texas Central), Abilene and San Angelo (AEP Texas North), Texas, as these are the larger cities in each service territory, thus likely to have local solar installers.

When pilot participants (utility residential customers) signed up, they filled out a pre-survey through which we captured their socio-demographic information and existing attitudes and knowledge of energy and solar-related measures. The information dissemination followed the pre-survey via two channels. The two mediums for the information campaign included: (i) a gamified information platform ("Energy Games") delivered over handheld devices and (ii) a conventional information campaign delivered electronically via email. At conclusion of the information campaign, participants filled out a post-survey to measure if and how attitudes, knowledge, and solar-related action (contacting other solar owners; contacting installers or utility; soliciting quotes; etc.) may have changed. We had a total of 567 unique initial surveys. We reserved 150 for the control group. 370

participants were invited to join Energy Games and 61 registered (16.5%). Of those 61, 40 downloaded the game (50% is typical), and 30 actively played the game. The 30 questions in the game were spread over two weeks, with 15 questions delivered to participants per week. Those participants in the pilot study that did not register for Energy Games received the same information presented in the game in the form of a survey (info-survey). After the Energy Games and the Info-survey information campaigns, we also conducted a post-survey ("final survey") to measure changes in knowledge, perception, attitude, and potentially behavior. We had 178 final survey responses, including 27 of 30 game players, 21 of 30 in the info-survey group, 74 in the control group, and another 55 that were invited to play the game but chose not to play and read the info-survey.

Findings from analysis of the initial survey data were published in a journal article in 2015 entitled "*Public Perceptions and Information Gaps Solar Energy in Texas*," (Rai, V. and Beck, A.L. 2015.) In this paper we studied individual-level perceptions and information gaps associated with the adoption of residential solar PV. Specifically, we collected and analyzed a new survey dataset of households in Texas to better understand existing attitudes, norms, and perceived behavioral control (PBC) and their impact on intentions and behavior regarding the adoption of solar PV. Our analysis shed light on the nature of behavioral and informational barriers in the adoption of residential PV in Texas and offers insights for designing potential interventions to alleviate those barriers. Survey respondents demonstrated positive attitudes, which were significantly associated with intentions to consider the adoption of solar PV. PBC was also highly significant in every model we tested for intentions toward considering solar installation or calling installers for quotes, though it was rated low (3.15). Low PBC toward solar may indicate why descriptive norms play such an influential role in considering solar. Since respondents do not feel particularly knowledgeable or confident with solar, a new and complex technology, looking to others for information and/or confirmation has relevance and benefit. Thus solar incentive programs should strive to leverage the beneficial impacts of peer effects (reflected in descriptive norms) to address underlying informational barriers in the adoption of PV. Further, influencing attitude and PBC through targeted information regarding the financial benefits could provide the necessary impetus at the early stages of the decision process regardless of environmental concern. But information alone, especially if not targeted, may not be sufficient to overcome adoption barriers. Survey respondents had the option of leaving a comment. The most frequent sentiment (57%) of those that did was that they would install solar if they could afford it, which is consistent with the reported high (positive) attitude but low PBC survey scores. This indicates a market ready for solar PV when systems become more affordable. For many, growth in the availability of solar loans and leasing options creates those affordable conditions and potentially opens new market segments in residential PV. However, despite the presence of federal (30% investment tax credit) and local incentives ($1.20/W) and leasing options, respondents generally expected low financial returns from solar. This suggests that customer awareness of the cost of solar has not caught up with available incentives and rebates, declining prices, and lease options that are quickly increasing the affordability of solar PV. This is a valuable insight, in light of the fact that our models show that perceived affordability of solar is the strongest predictor of intentions associated with adopting solar. That a population with higher than average educational attainment – a factor generally indicative of more informed respondents – showed such low awareness of solar costs, options, and investment potential, points to a substantial information gap that is likely feeding the low observed PBC in the sample. One implication of these findings is that incentives to encourage solar PV adoption would be more effective if accompanied by relevant information that enables the targeted population to assess how the incentives actually impact key criteria, such as affordability, and to update their perceptions accordingly.

Findings from the *Energy Games* RCT information campaign have been presented in a working paper (Rai, V. and Beck, A.L. 2016), which is also currently under peer-review. Our findings support the effectiveness of serious games in bridging the information gap and enabling participants to feel agency. We show that serious games offer a holistic approach to addressing information asymmetries, as they can confront misperceptions, reduce information search costs, and challenge multi-dimensional information gaps, all known barriers to the adoption of energy conservation and solar. Thus, applied at a large scale serious games could prove effective in activating the passive customer base, helping unlock emissions reductions in the residential sector.

The effectiveness of Energy Games is likely due to a combination of three factors. First, the trivia-style game *confronts misperceptions* by requiring that players definitively choose an answer and then receive clear, immediate feedback of whether they are correct, rather than more passive means of receiving information (e.g., a pamphlet or newsletter) that leaves the content vulnerable to confirmation bias or the ostrich effect. Second, by providing distilled, actionable information Energy Games *reduces information search costs*, a recognized barrier to energy conservation behavior and solar adoption, since the average participant only spent a total of 22 minutes playing the game to achieve significant gains in PBC and other attributes. Third, Energy Games *challenges multi-dimensional information gaps* by chipping away at a broad scope of dimensions, such as attitudes, norms, costs, benefits, and performance. Such combined effects are known to be effective in inducing energy-related behavior change. Confirmation that these mechanisms are causative for the exact nature of the effectiveness Energy Games will require additional study, as this initial study seeks primarily to demonstrate effectiveness that warrants further study.

Furthermore, that PBC was addressed most heavily in the content and exhibited the most significant change among the antecedents, while attitudes had middling changes and norms had the least change, indicates that the impact of Energy Games is directly related to the composition of the content. Thus Energy Games may offer a flexible mechanism for targeted intervention by varying the proportion of the content. Additionally, we note that influencing PBC, a direct antecedent to both intentions (an immediate antecedent of behavior) and behavior, will have an amplified impact on behavior. Thus, that Energy Games significantly and consistently increased PBC and intentions for both solar energy and energy conservation supports the effectiveness of serious games in addressing information gaps and facilitating energy-related behavior change. Overall, by effectively addressing information asymmetries, Energy Games helps participants feel agency and may “activate” the passive potential customer base for unlocking emissions reduction in the residential sector.

C. Pilot 2: Installer Bidding and Customer Behavior on an Online Marketplace

We worked with an online PV information portal and marketplace for PV installers and buyers, on creating a database of quote and installer data across its national operations. The broad scope of analysis within this pilot has enabled the generation of novel insights about how online marketplaces are being used and are impacting the residential PV market.

This dataset is a unique national database of solar installation quotes offered to potential solar adopters. This data allows for insights based on inputs, i.e., installer quotes, to the decision making process rather than the outcomes, i.e., installed systems. Our work with this dataset included completing three tasks: (i) an overview of descriptive data, (ii) an analysis of installers using this platform compared to those in a national database, and

(iii) two models of consumer behavior. The first model looks for differentiating variables between quotes for properties that adopted solar through the online platform in order to determine which attributes of a quote increase the likelihood of selection of a quote provided through the online platform. The second model looks at the quotes for each property as group of quotes with the independent variables representing the mean, range, or variance in quotes received by a single household in order to explore characteristics of the quotes as a group that influence solar adoption by the property owner. The goal of this analysis was to explore how the online marketplace is being used, who is using it, how the quotes have changed over time, and the characteristics of the quotes that impact solar adoption decision-making.

This dataset provided a unique opportunity to investigate how the attributes of quoted systems impact the decision making process of solar adoption and quote selection. Overall, customers using this marketplace were more likely to purchase with cash or loan than the national average. The installers using this marketplace were smaller than the national average. The overrepresentation of cash purchases may be related to the smaller installers not providing loans or leases, resulting in a marketplace uniquely suited to matching smaller local installers with the right market segment of solar customers.

The system characteristics of *quoted* systems on the marketplace were nationally under $2.50/W *net price* (to the customer) and 7.5kW, providing an electricity offset of 84%. However, an important note is that this does not necessarily indicate the final installed system specifications. Based on model results, customers select for lower cost per watt, lower system size (likely due to lower overall system cost), and higher electricity offset. Customers showed a preference for string inverters, but market share of advanced inverters were increasing in 2015. From this data it is not clear if the preference for string inverters is related to lower cost or being a more established technology, or some other unidentified factor. The top five inverter manufactures in the dataset accounted for 90% of quoted inverters. Customers generally preferred lower cost panels, with preference for recognized brands (such as LG and SunPower). The top five panel manufactures represented 61% of quoted panels.

The time lag between submitting a property to the online marketplace and receiving a quote proved significant in determining if the customer decided to accept a quote through the platform. It is notable that selection preference went to later arriving quotes, which may be related to the most recent quote being most salient. Installer estimated install time was also statistically significant, but had a much smaller coefficient than quote time (lag). The number of quotes received also proved significant in the quote group models, which indicates that later arriving quotes may serve as a reminder to make an adoption decision. However, the significance of quote count may also be related to receiving more options, thus the right fit, or reflect that installers have identified the homes most likely to benefit from and/or adopt solar. We did not have any information on demographics, home size, or specific location to control for these variables. The quote group model also revealed that those customers who viewed an instant estimate for installed cost and potential savings were more likely to adopt.

D. Directions for Future Research

D1. Modeling of Residential PV Adoption

Agent-based modeling offers a unique ability to model the decision-making of heterogeneous agents with bounded rationality. However, this requires careful model design, implementation, and validation. The rigor of the modeling process will determine the robustness and applicability of any insights gleaned from ABM. Solar adoption is a complex process, including agent-level economic, attitudinal, and social factors. Models that include all of these components fit the data better and generate more realistic emergent patterns. Most importantly, models that focus solely on the financial aspects of agents' decision-making do well in generating the rate of adoption and the cumulative adoption curve, but do not perform well on spatial and demographic patterns of adoption. Thus incorporating agents' attitudinal aspects and social interactions becomes critical when seeking high spatial and demographic accuracy of the model. Furthermore, as noted before (Section III.A.3), it is important to use multiple validation checks in assessing the performance of the different models considered.

Rai & Henry (2016) provide a detailed discussion on directions for future research focusing on ABM for consumer energy choices. The key highlights are as follows (Rai and Henry, 2016):

1) By far the most commonly-studied question using ABM in energy involves consumer adoption of sustainable energy technologies and behaviors. These ABM studies predominantly focus on questions about policy design and evaluation; they analyze how variations in policy instruments and marketing or communication strategies impact the rate and scale of adoption. In contrast, relatively little attention has been paid to questions of system design and planning, dealing with implications for the nature of electricity demand and infrastructure. This is a fertile area for future research.

2) Only a few studies analyze the comparative performance of different theories or theoretical elements in addressing the same empirical application. However, it is important to ascertain what tasks can other modeling approaches do or not do reliably within given confidence intervals, and how much better ABM-based techniques are at the same tasks. To accomplish this, more work is needed that directly compares the performance of non-ABM methods with those of ABM to model the same problem with similar rigor and empirical detail.

3) An important driver for many energy-related ABM studies is the potential that ABM offers in generating emergent outcomes through the dynamic interactions of agents – that is, in illustrating the linkage between 'micromotives' and 'macrobehaviors'. While most energy-behavior ABM studies note this advantage of ABM and go on to generate emergent outcomes (for example, adoption curves), only some of those studies actually focus on analyzing how factors such as network structure and agent interaction processes influence emergence. We expect future ABM studies to focus more on effectively leveraging ABM's capability for analyzing emergence.

4) The current ABM work in the area of energy-related consumer behavior is weak in spatial representation. Models of energy behavior need to realistically account for underlying social interactions, as well as the heterogeneity of agents and their interactions over space. For certain new energy technologies, the (limited) information set of agents may have a pronounced spatial character. Without knowledge of such empirical patterns a modeler might wrongly specify the network structure and end up with an invalid model for the system as a whole. Thus to represent agent interactions appropriately it is important that the relevant network structure be derived from empirical patterns gleaned from the data rather than simple assumptions or convenient distributions. Resolving the paucity of energy-focused social network data should be a priority area for researchers studying energy behavior.

5) The most limiting weakness, almost across the board, is the lack of careful validation of the built agent-based models. Overall, rigorous validation of agent-based models before addressing questions of policy design is critically important and an area that demands priority attention of ABM research in energy demand.

6) Development of ABM techniques with good predictive capabilities requires detailed, relevant data, and building these datasets requires resource-intensive approaches that require use of individual-level data. Given that such opportunities for large-scale, deep data collection are relatively hard to come by, such efforts could benefit from coordination among researchers to identify priority data elements to collect and share more broadly, with careful attention to the ethics of human subjects research. Policymakers, regulators, and funding agencies also have a role to play here. Better policy design involves experimentation to understand the dynamics of the underlying system. Policies and regulators need to proactively create such opportunities for researchers to be able to generate real-world knowledge through research. Finally, efforts need to be made to help the public understand the importance of such research efforts and the safeguards in place to protect data. A more open, inclusive discussion about these issues is more likely to generate broad public support and acceptance of large-scale, longitudinal studies of energy demand.

D2. Addressing Information Gaps on PV Adoption

Our prior studies in this area[1] (Rai & Beck 2015; Rai & Beck 2016; Beck et al. 2016) indicate that receiving multiple messages with smaller amounts of information increase the time spent viewing the information and result in an increase in perceived behavioral control (PBC), a key antecedent of intention and behavior, compared to receiving all information at once. Additionally, our experiments using serious games – games with a primary purpose other than entertainment – show twice the increase in PBC and 50% greater increase in intentions for participants compared to the multi message experiment. However, while these studies used systematic and rigorous research design (including randomized control trials and a theoretically based survey instrument), comparing results across multiple experiments limits our ability to draw generalizable, overarching conclusions. Accordingly, there is need to conduct large scale, integrated experiments that explore all these factors within a close-knit set of experiments, so that the robustness of the findings, effect sizes, and durability of results can be established in an unambiguous manner. The key research questions to address in future research include:

1) How durable are the impacts of information on the antecedents of intention and behavior? How does durability change based on the mode (passive vs. interactive) of information?
2) What are the optimal quantity, frequency, and content of information to deliver to maximize engagement and reduce audience fatigue? Do these optimal points vary based on information mode?
3) Does the mode of information delivery affect the likelihood of continued information search (e.g., measured through click rates on provided links)?
4) What are the long-term (over several months) impacts of the information modes on solar adoption behavior?

[1] **Rai, V. & Beck, A.L.,** 2015. Public perceptions and information gaps in solar energy in Texas. *Environmental Research Letters*, 10(7), p.074011. Available at: http://iopscience.iop.org/article/10.1088/1748-9326/10/7/074011. **Rai, V. & Beck, A.L.**, 2016. Serious Games in Breaking Informational Barriers in Solar Energy. *SSRN*. Available at: http://ssrn.com/abstract=2816852**; Beck, A.L., Lakkaraju, K. & Rai, V.**, 2016. Small Is Big: Interactive Trumps Passive Information in Breaking Information Barriers and Impacting Behavioral Antecedents. Available at: http://ssrn.com/abstract=2823952

D3. Online Marketplaces

For online marketplaces, we suggest three directions for future research:

1) The relevance of the instant estimate in increasing the likelihood of adoption is interesting, but the mechanism at work is unclear. Thus investigating if the instant estimate is providing a filter for more serious customers or providing an anchoring point for considering future quotes would be informative.

2) Comparing the selected quoted system to the final installation would provide insight into the front to back decision making process, such as which system characteristics are most desirable upfront versus after more careful consideration and discussion with the installer. Additionally, comparing these systems to LBNL's Tracking the Sun (TTS) dataset would allow analysis of if and how the installed systems acquired through the online marketplace vary from those acquired through other channels.

3) A cluster analysis of quoted (online marketplace) versus installed (TTS) systems could indicate how packages of equipment options vary between quotes and final installs.