SIMULATION OF SOLAR PANEL ADOPTION USING AGENT-BASED MODEL: A CASE STUDY OF CALIFORNIA

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Overview:
As stated by National Aeronautics and Space Administration (NASA), California is one of the states with the highest solar irradiance in the United States. Government supportive renewable energy programs and compatible climate increase popularity of solar energy use in California. According to the Federal Energy Regulatory Commission report, in California, there is 50% electricity supply coming from renewable energy, 40% of which is solar power, indicating a huge potential to promotion solar panels. Set to take effect in 2020, California Energy Commision (CEC) gave final approval to mandate solar panels to be installed in all new homes up to three-storeis-high with the goal of building homes that are more realiable and efficient while facing recent exterme weather events. In order to understand the decision making process on solar panel adoption, and attract more home owners to install solar panels, we develop an agent-based model to simulate people's behavior and interaction, then explore possible outcomes emerged in the complex adaptive system. We model agent groups including home owners, solar panel providers, utilities, and regulators. Preference, salience level, and basic demographic data is used as inputs, while different policies and strategies are used as policy levers in simulations and sensitivity analysis. Both cooperative and non-cooperative game theory applications are also adopted in modeling agents interaction and expected utilities calculated.

Methods
Agent-based model

Conclusions
We expect to identify the most influential factor on solar panel adoption decision making, and make policy recommendations on how to promote solar panel adoption to achieve California’s ambitious carbon-neutral energy goal within the next 30 years.
1. Introduction

Achieving solutions to electricity generation problems that we face today requires long-term investigation on the connection between sustainable development and renewable energy sources. In light of the increasing scientific consensus on global climate change and the desire for greater energy security, many governments have recently set ambitious targets to increase the share of renewable energy in the total energy mix. California has become one of the leading states in implementing policies and providing financial incentives promoting the use of solar photovoltaic (PV), initiatives vary from state-level, county wide and municipal levels. The ultimate goal is to increase solar power accessibility for all and distribute savings opportunities with government supported programs designed for households under different income levels.

Past research has shown that adoption of solar energy can, in most circumstances, reduce cost and greenhouse emission ($CO_2$). Recent years, with renewable energy seen as a critical step towards sustainable development, the production and installation of solar PV have significantly decrease in cost allow the option to adopt become more affordable to most households. Furthermore, another distinct benefit of solar source is that it can be implemented on a larger scale across cities (Arnette 2013). In California, solar energy has provided 19.02% of state electricity, created 76,838 employment opportunities, and installation price has decreased 34% within the last 5 years (SEIA Factsheet 2018). Based on these empirical evidences supporting the ease in adoption from monetary barriers to solar energy source, social interactions between consumers becomes particularly interesting because individual preference can have spillover effect to influence other agents’ decision to adopt and comply with solar PV system. Traditional theoretical framework of social contagion is used to describe the role of “positive influence” played in behavioral changes (Bass 1969), but the emphasis on interaction may not fully capture the effect of cost-benefit behind individuals’ preferences.

This paper makes several contributions expanding literature on social interaction to include cost-benefit analysis with profitable feedback affecting the formation of individual preferences and finally influence other agents into adoption of solar PV. Methodologically, we adopt Agent-Based Modeling approach for a simplified estimation of adoption rate, leveraging simulation process to capture the preferences formed on the basis of economic factors and demographic characteristics, finally influencing other agents in decision making to switch to solar renewable energy.

2. Literature Review

Majority of literature background and scholars have proposed researches on residential solar energy using cost benefit analysis to investigate break-even point for individuals’ investment in paying higher cost in early adoption of PV with long term savings opportunities in utility spending and tax incentive programs. Research shown that
California Solar Initiatives (CSI) rebates have a large effect on residential PV adoption, empirical evidence suggests an increasing rebates from $5,600 to $6,070 would increase installations by 10%. (Hughes and Podolefsky 2015). The results from these research provide additional support in evaluating government programs promoting green cities promoting energy efficiency in residential and commercial buildings (Kahn and Kok 2014). However, previous theories and research methods have limited reach in investigating personal characteristics and interactions. Thus, this paper contributes to a larger literature on cost benefit analysis allowing realistic decision making process on solar adoption among individuals.

The emergent pattern of behavior changes, individual influencing others to switch to solar PV system, cannot be understood without a bottom up dynamical model of the microfoundations at the relational level. In this research, we adopt ABM, a flexible simulation technique, considering economic factors (i.e. utilities savings) and interaction to illustrate a decision making process for individual to successfully influence another agent’s behavior. According to Bonabeau, “the broader agenda of the ABM community is to advocate a new way of approaching social phenomena, not from a traditional modeling perspective but from the perspective of redefining the scientific process entirely (2002).” ABM is extremely useful in mapping between preferences and behavior interact with local environment constraints. Specifically, ABM differs from traditional sociological research methods lies in the computational simulation incorporate personal characteristics allowing agents to gain valuable resources, for instance, potential savings from solar PV system.

The objective of this paper is to provide a fundamental, yet complex, social influence model which emphasizes on interaction and preference based on demographic data with different policies, strategy and comparison between capital investment and utilities savings used as levers in simulations and sensitivity analysis.

3. Research Design

This research focuses on understanding the effect of interactions in a changing environment that individuals constantly make decisions to reach their goal in achieving utilities saving though solar PV system adoption. Based on this central idea, we employ ABM to simulate model component (individual level) to observe corresponding influenced by preferences changing and the behavior change determined by solar adoption rate, further mirror the behavior change in a real system. ABM is a simulation computational method where individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment locally.

The traditional statistical methods are often used to test hypotheses and predict through equation modeling in a structured environment, but the complexity of differential equations increases exponentially as the complexity of behavior increases. On the other hand, individual behavior is complex in the real world, we cannot fully explain people's behavior without a network-like structure. Therefore, describing complex individual behaviors with equations becomes intractable. Hence, using ABM to use simulation to search for causal
mechanisms that may underlie statistical associations by setting up principal which we seek to understand for policy adoption or information diffusion is the most suitable method in the case of investigating the effect of interactions to behavioral changes from traditional energy sources to solar PV systems.

Figure 1 demonstrates our model structure. First, we set up agents’ personal characteristics and demographic information including income and education level. The model explicitly represents a logical decision-making process considering the cost and benefit of solar adoption to an individual’s economic interest. Second, we calculate agents’ satisfaction stems from utility savings with solar panels installed. Third, preference formation after we set up the threshold to compare previous savings potential to the actual savings achieved after solar panels installation. Lastly, how the public’s interaction with each other in line with their preferences and we can simulate how solar panels adoption change over time.
4. Model, Entities and Variables

Pseudo code:

For each resident {
    Update own preference based on individual attributes and global variables
    Calculate electricity bill (usage * price)
    Calculate solar panel installation cost and benefit
    If solar panel installation benefit > electricity bill + installation cost
    Then Preference increase
    Else preference decrease

    Decide whether to interact with another resident
    based on geographic distance and ideological distance
    If probability < threshold
    Then no interaction
    Else For each interaction {
        Update preference and influence power
    }

    Decide whether to adopt solar panel
    If preference < threshold
    Then do not adopt solar panel
    Else If wealth level < threshold
        Then do not adopt
        Else adopt
}

Update global variables based on resident agent attributes

Figure 2. Detailed description of the concept used in NetLogo.

Our model is deployed in NetLogo, a graphic user interface which allows an advanced programmer to visualize algorithms, we explore agents’ behaviors under different scenarios with set boundaries. Here we will demonstrate the application of NetLogo to model individual level entities and features (Figure 2). State variable includes talkspen (the maximum distance that agents can effectively communicate with corresponding influencing power), and preference. One of the benefits to solely focused on one level is that this provides us with a simplified environment further magnify the key features we are investigating, i.e. demographic characteristics interacting with the length of a conversation, at different relationship dynamic. Next, we combine the use of cost-benefit analysis to mimic a human’s natural instinct in choosing according to personal economic interest. We use average electricity saving after the pubic installed solar panels as $128 dollars/ monthly.
If agents install solar panels and could save more than $128 dollars each month that will increase their preferences vice versa.

For the first entity, we select a geographic location, income, education level, utility usage, and electric price. The environment is a representation of a fictional state (network), and each agent is randomly placed within the network (based on the normal distribution).

Second, individual residents are also characterized by few dynamic variables which are tempered by differences in societal classes, (education * wealth, normalized between 0 and 1) defining preference (wealth * wealth trend * education) and influence power (income * education * proximity * random term =2). The next step in the process is to define feedback and proximity, a function of physical distance and ideological (preference) distance. The calculation of proximity allows us to estimate the likelihood an agent can create influence on others through information sharing on benefits gained from a solar PV system. An emergent class of entities is the community bargaining organizations (potentially including opposition groups) that form when citizens coalesce around shared interests in maximizing utility savings. Build on previous theory and research that social influence reduces decision anxiety for others and may further increase the acceptability of the consumption decision.

Each individual agents have attributes which are calculated by dynamic state variables. The calculation of agents preference and power is described in the previous paragraph; individual preference is the weighted preference if that individual ends up in a group. Both agent types have utility as one of their main attributes, the logic of which follows Bilateral Shapley Values (BSV) that will be used in the bargaining process. Utility bill we defined as a function of usage and electricity price.

When agents A stays alone, utilityA = (100 – ABS (prefA – prefA)) * powerA; when A and B form a , utilityAB = (powerA + powerB) * 1.5 * (100–ABS(pref A–pref B)). For the individual agent A in this AB coalition, utility is calculated as utilityA(AB) = 0.5 * (V (A) + V(AB)utilityA + utilityAB).

Since the bargaining power is unevenly distributed among agents, the function is defined to capture the expected utility individual can save thus and its role in the overall cooperation thus making adoption decision based on a calculated expected payoff.

Here we consider the general problem of a set of agents who negotiate in pairs. All agents may be linked initially, or certain links may not be possible for exogenous reasons. These links define the initial information transferring network. Our environment is constructed as such pairs of agents interact over common interest (i.e. cost-saving opportunities through solar PV adoption) which is jointly observable from the change in the utility bill. The behavior may first only include individual action undertaken by one again but observed by another (diffusion theory). We specify in a non-cooperative game where each pair of agents in the structure network interacts and decide their best interest based on payoff function is to not make changes to their existing electrical system.

In our overall process, the perceived characteristics affect adoption decisions at two levels. When an agent becomes aware of a savings opportunity, perceived characteristics will be assessed at the individual level first. If the individual decides to change, perceived
characteristics will be assessed at the overall profitability level next, which will influence the actual adoption decision. The factors the individual will consider when making an adoption decision vary depending on whether the assessment is at the individual or overall level. At the individual level, characteristics that broadly define the utility savings, such as compatibility (to the current design of their home), sustainability, observability, and perceived risk, will be considered. The second part of the actual behavior change process, or the overall level decision, is evaluated by profitability (calculated from cost-benefit) and further extend to their power of influence over other agents.

5. Preliminary Results

In figure 3, we could see, when solar usage increasing which the electricity prices are getting lower over time. That also means, when more people install solar panels which would help electricity saving. Moreover, part of residential areas generates extra power could be sent back girds that would help users save more utility cost. In another point of view about solar panels installed numbers(monthly), in figure 4, we could see the prediction of installations show in a stable trend. The trend indicates the cap of installation numbers, still, not many residential areas employ solar panels. However, the prediction numbers not consider the public’ interaction, which is an improvement we could complement by ABM.
6. Discussion

The local state government in the United States have made active commitments towards developing low-carbon economies and to promote sustainable development. Generating renewable energy using solar PV system help government meet long term sustainable goals, especially in the case of California, aligning the state’s ambitious goal of zero-emission in electricity by 2045 (Figure 5). In this paper, we have created a model for future researchers to further evaluate the factors influencing residents’ decision-making process to the action of adopting solar PV system using readily available environmental, economic, and social demographic data. In addition, we provided a detailed description of our ABM module to illustrate a focused design on an individual level to clearly map out the effect of interaction and influence have on expected utility between agents.

Through our research requires more effort in the completion of the simulation, our initial results have provided evidence that various factors play an important role in the decision-making process of adoption rate to solar renewable energy. Specifically, talkspan, which determines the range of each individual agent’s social interaction, in combination with personal characteristics (i.e. income level and education) determines a weighted preference under the condition that the individual becomes jointly in a group thus creating an influencing power over other agents. We believe the ability to communicate makes it easier to share information and decrease barriers to change, in our case, a key linkage to define the reach of influence. Furthermore, incorporating BSV enable us to fully capture the overall strategic interaction in an imperfectly balanced environment allowing us to calculate the respective expected utility for each player from the formation of individual-level preference.
7. Limitation and Extension

While our model provides us a logical approach to investigate the decision making process through empirical data, greater accuracy can be achieved in the future as the relevant data needed relating to solar renewable energy source become available over time. The research result can be greatly improved with additional data including a more accurate assessment of household energy costs, separating residential and commercial usage, including financial incentives provided through government, supported programs and at a finer level of granularity.

Figure 5. Solar Resource of California Map from the National Renewable Energy Laboratory (NREL)
Reference