Drivers of Residential PV Adoption:  
Toward Predictive Modeling and Understanding  
Infrastructure Implications  

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What Drives the Spatio-Temporal Patterns of Energy Technology Diffusion?

**Agent-Based Modeling of the Rate and Structure of Solar Adoption**

**Model Scope:**
City of Austin, TX

~170,000 households

~3,000 PV Adopters (1.8%) as of Q2 2013

**Initialization Time Period:**
Through Q4 2007

**Validation Time Period:**
Q1 2008 – Q2 2013
+ Q3 2013 – Q4 2014
Solar Agent-Based Model (ABM)

Agents

Explicitly coded composite (theoretical) decision rules:

D1) I only adopt if I think going solar is a good thing (beliefs): $\text{Attitude}_i > \text{Global threshold (}\Phi\text{)}$

D2) I only adopt if I can afford solar (controls): $\text{PP}_{it} < \text{pbc}_i$

I get information about solar through my social network (Relative agreement model)

Figure 1: Flowchart describing the solar ABM structure, emphasizing the agent decision process to install solar. Agent decision rules are based on attitudinal and economic factors, with social influences playing a role in the adoption process. The model illustrates the interaction between agents, their attributes, and the various criteria influencing adoption decisions.
# Which Model Components are Most Critical for Accuracy? Four Model Variations

<table>
<thead>
<tr>
<th>Social interactions</th>
<th>Structure of social networks</th>
<th>Resolution of irradiance data</th>
</tr>
</thead>
</table>

## Model Features

<table>
<thead>
<tr>
<th>Model</th>
<th>Initialization</th>
<th>Social Network</th>
<th>Attitudes</th>
<th>PV Economics</th>
<th>Irradiance Resolution</th>
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</thead>
<tbody>
<tr>
<td>Base-case</td>
<td>Empirical</td>
<td>Yes (SWN)</td>
<td>Yes</td>
<td>Yes</td>
<td>Household</td>
</tr>
<tr>
<td>Simple Environment</td>
<td>Empirical</td>
<td>Yes (SWN)</td>
<td>Yes</td>
<td>Yes</td>
<td>City</td>
</tr>
<tr>
<td>Economic Only</td>
<td>Empirical</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Household</td>
</tr>
<tr>
<td>Random Fitted</td>
<td>Random</td>
<td>Yes (ER)</td>
<td>Yes</td>
<td>Yes</td>
<td>None</td>
</tr>
</tbody>
</table>

All simulations were run on the 10PF Stampede Supercomputer at the Texas Advanced Computing Center (TACC), utilizing 16 tasks per server node (each with two 350GF Intel Xeon E5-2680 processors and one 1070GF Intel Xeon Phi SE10P Coprocessor) on 100 nodes per batch (1 batch = 100 simulations). Depending on the exact specification, each batch took between 20 and 35 minutes to execute.
Determinants of Spatio-Temporal Patterns in Adoption

Fit to minimize cumulative

\[
RMSE = \sqrt{\frac{\sum_{q=1}^{n} (\hat{a}_q - a_q)^2}{n}}
\]

- **Financial aspects** of the solar-adoption decision performs well in predicting the rate and scale of adoption.

- Accounting for agent-level attitude and social interactions are critical for predicting spatial and demographic patterns of adoption with high accuracy.
Demographic Validation

Validation Metrics

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<th></th>
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</thead>
<tbody>
<tr>
<td>Base-case</td>
<td>76.93</td>
<td>0.46</td>
<td>0.43</td>
<td>0.86</td>
<td>110,580.2</td>
<td>-37,967.7</td>
<td>0.81</td>
<td>0.81</td>
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<tr>
<td>Simple Environment</td>
<td>106.91</td>
<td>0.99</td>
<td>0.42</td>
<td>0.56</td>
<td>162,436.7</td>
<td>109,296.8</td>
<td>0.73</td>
<td>0.74</td>
</tr>
<tr>
<td>Random Fitted</td>
<td>65.95</td>
<td>-1.09</td>
<td>0.34</td>
<td>0.46</td>
<td>113,289.5</td>
<td>-88,463.62</td>
<td>0.77</td>
<td>0.76</td>
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<tr>
<td>Economic Only</td>
<td>88.60</td>
<td>1.37</td>
<td>0.41</td>
<td>0.55</td>
<td>157,047.6</td>
<td>147,748.8</td>
<td>0.74</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Prediction Accuracy

~5%

Figure 5: Fit and predicted model outcomes compared to empirical data. Observed adoption levels are shown by the gold line. The purple line shows the Integrated Model, described in Section 4.1. The average of the six quarter forecast (Q3 2013 - Q4 2014) is shown as the red dashed line (Section 4.1.1). The points represent individual model runs. No parameters were altered or fitted to data after Q2 2013.
Predicted Capacity and Spatial Density of Residential Solar PV Adoption in Austin by 2025 (Scenario: Baseline)

Model 1709 parameters: FITC declines to 0.10 in 2017, VoS 11.3c/kW, Rebates decline by 20% annually ending 12/2020, Installed costs decline by 4% annually

Total Capacity 2020: 26,623 kW
Total Capacity 2025: 29,418 kW
Total Adoptions 2020: 5,147
Total Adoptions 2025: 5,452
Predicted Capacity and Spatial Density of Residential Solar PV Adoption in Austin by 2025 (Scenario: Optimistic)

Total Capacity 2020: 37,836 kW
Total Capacity 2025: 43,436 kW
Total Adoptions 2020: 6,705
Total Adoptions 2025: 7,330

Model 1712 parameters: FITC stays at 0.30, VoS 11.3c/kW, Rebates decline by 20% annually ending 12/2020, Installed costs decline by 10% in 2015 & 2016, by 4% otherwise1

CAGR ~15% across a range of scenarios
### Installed Cost vs. Cost of Ownership

#### Buyers:
- Mean: $6.2/W
- SD: $1.4/W

#### Leasees:
- Mean: $8.3/W
- SD: $0.53/W

#### Installed Costs (No Rebates)

<table>
<thead>
<tr>
<th>Cost (W)</th>
<th>Bought</th>
<th>Leased</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4/W</td>
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<td></td>
</tr>
<tr>
<td>$5/W</td>
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<td>$6/W</td>
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<td>$7/W</td>
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<td>$8/W</td>
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<td>$9/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$11/W</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Cost of Ownership (After Rebates)

<table>
<thead>
<tr>
<th>Cost (W)</th>
<th>Bought</th>
<th>Leased</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2/W</td>
<td></td>
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</tr>
<tr>
<td>$3/W</td>
<td></td>
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<td>$4/W</td>
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</tr>
<tr>
<td>$5/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6/W</td>
<td></td>
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</tbody>
</table>

• Huge gap between attitude (5.31/7) and perceived affordability (3.15/7) of solar
  – Perception of ability to afford solar low (3.15 on a 7-pt Likert scale)
  – Solar perceived as expensive due to incomplete information about performance, leasing, and incentives
    • Only 16% reported awareness of any incentives
  – Addressing info gap could open up large potential demand

• We conducted a game-based experiment ("Energy Games") primarily targeted at the perception of affordability and financial aspects of solar
Residential EE & Solar Adoption Behavior: An Online Gamification Study

What does your solar system do when it produces more energy than you use?

- Turns all the lights on
- Sends it to the grid
- Shuts the system off
- Signals the international space station
“Energy Games” Content

• **Topics: Energy conservation and solar PV**
  – **Energy Efficiency Behavioral Measures**: thermostat setting, water heater setting, vampire power, washing machine water temperature
  – **Energy Efficient Equipment Upgrades**: ENERGY Star appliances, LED lighting, Insulation, Ductwork, Door and window seals
  – **Solar PV Systems**: Technology basics, Cost, Leasing option, Incentives/rebates

• **Length – 2 Weeks**
  – **Week 1**: Small Changes, Big Savings! (15 questions: 5q x 3days)
  – **Week 2**: Big Changes, Bigger Savings! (15 questions: 5q x 3days)

• **Communication**
  – Reminders to play
  – Follow-up emails (1/week) summarizing key info
Energy Games: Impact

• The interactive nature of a trivia game tests respondents perceived knowledge
  – More “aha” moments (vs. say a newsletter) with the gamified version ➔ Higher perceived affordability

• Awareness of incentives significantly increased, which indicates that incentive programs may not be well publicized for passive audiences

• Likelihood of calling to request a solar quote increased following the game. This is one of the key factors to influence as it is a critical and necessary hurdle in the solar adoption process
Other Emerging Drivers

- **Increasing awareness** of solar driven by
  - Social processes
  - Active marketing by installers

- **New products**
  - Low-interest and “lease-like” **loan products**
  - Innovative **rate plans**
    - MP2/Solarcity, “true net metering” residential plan around Dallas-Fortworth
Acknowledgements

• Research funded by the Department of Energy’s SunShot Initiative under the Solar Energy Evolution and Diffusion Studies (SEEDS) program

• Austin Energy

• Texas Advanced Computing Center (TACC)
References

• Two ABM papers on the predictive modeling of solar diffusion are available at:
    – http://bit.ly/PatternsOfAdoption
  • Rai, V. and Robinson, S.A. Agent-Based Modeling of Energy Technology Adoption: Empirical Integration of Social, Behavioral, Economic, and Environmental Factors.
Integrated Decision-Making Framework Based on Deep Data and a Suite of Analytical Tools

- **Household-level Data**
  - Adopter and non-adopter
  - Surveys
  - Appraisal district rolls
  - Solar program data

- **Multi-method**
  - Econometric analyses
  - Financial modeling
  - GIS-integration
  - Agent-based modeling (ABM)
## Multiple, Matched Datasets

<table>
<thead>
<tr>
<th>Source</th>
<th>Content</th>
<th>Scope</th>
<th>Scale</th>
<th>Resolution</th>
<th>Time frame</th>
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</thead>
<tbody>
<tr>
<td>Austin Energy</td>
<td>System details, location, installation date, etc</td>
<td>PV Adopters</td>
<td>Population</td>
<td>Household</td>
<td>2004-2013</td>
</tr>
<tr>
<td>UT Austin</td>
<td>Survey responses regarding installation decision</td>
<td>PV Adopters</td>
<td>Sample, 22.5%</td>
<td>Household</td>
<td>2011-2014</td>
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<tr>
<td>TCAD</td>
<td>Home value, parcel size, land use code, etc</td>
<td>Land parcels</td>
<td>Population</td>
<td>Household</td>
<td>2013</td>
</tr>
<tr>
<td>CAPCOG</td>
<td>LIDAR images</td>
<td>City of Austin visible above ground</td>
<td>Population</td>
<td>6in</td>
<td>2013</td>
</tr>
<tr>
<td>USGS</td>
<td>National Elevation Dataset</td>
<td>City of Austin elevation ASL</td>
<td>Population</td>
<td>3m</td>
<td>2013</td>
</tr>
</tbody>
</table>
Application: Scenario, Tiered Rebates

Lower income quartile, everywhere, $0.25/W more

Everyone in a target zip code, $0.25/W more

Localized adoption increases from <1% in base-case to ~11% in Sc.328
Experiment Overview

- Use **initial survey** to capture existing attitudes and intentions regarding **energy conservation and solar**, as well as other controls.

- Create two **randomized** cohorts:
  - Control
  - Treatment (Gamified information)

- Employ **trivia-style mobile gaming platform** to succinctly deliver key information to the Game cohort.

- Use **final survey** to capture changes in attitudes and intentions regarding energy conservation and solar, and perceived effectiveness of gamified platform.
Game Platform: Ringorang®

- A **clue** gives a little hint for players new to energy topics
- A **question** conveys actionable or educational information
- An **insight** provides more context or information about the topic

- A “learn more” link to a web site for additional research or information on incentives
- A sliding scale for **points** based on how quickly you answer
- A **leaderboard** to compete with other players