Drivers of Residential PV Adoption:

Toward Predictive Modeling and Understanding Infrastructure Implications

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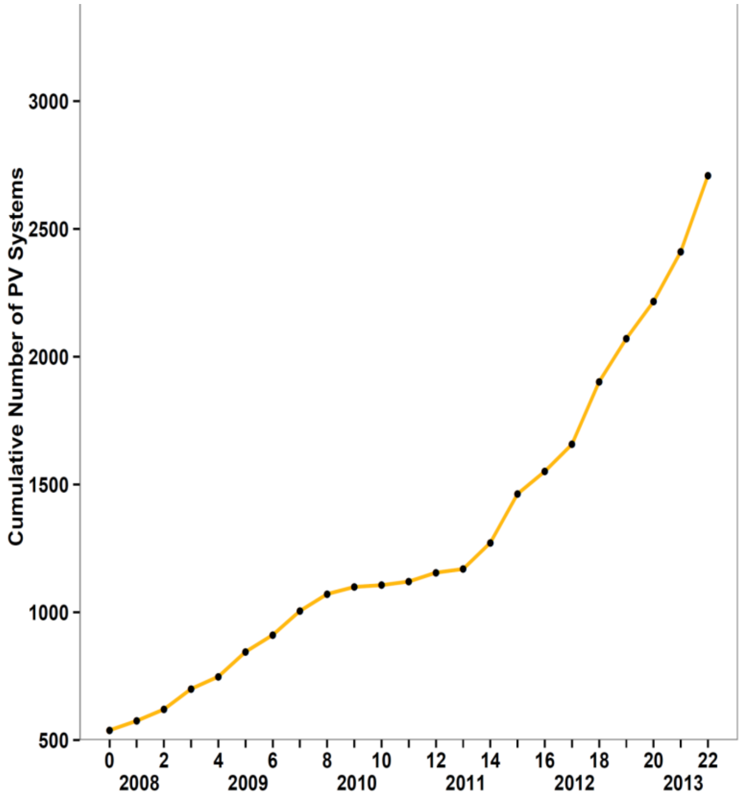
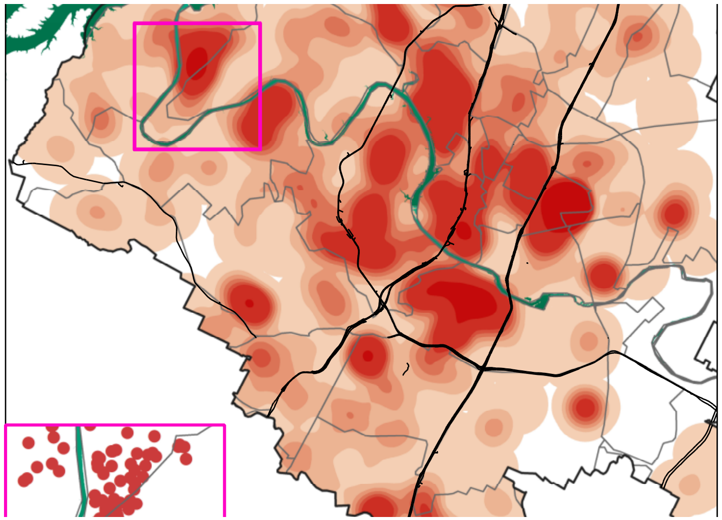
What Drives the Spatio-Temporal Patterns of Energy Technology Diffusion?

***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:

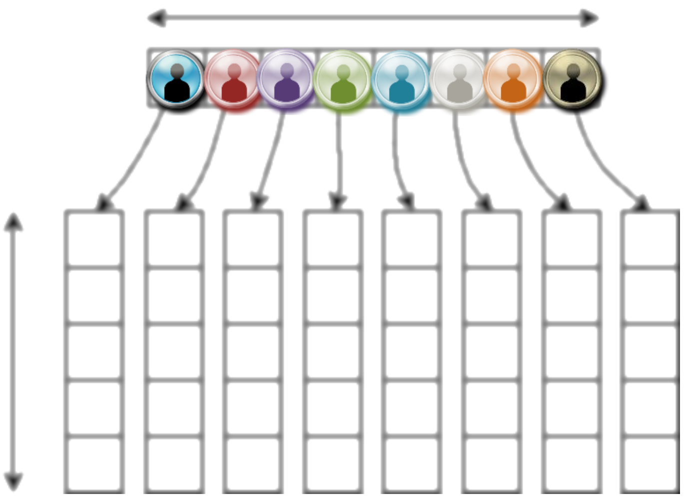
Q1 2008 – Q2 2013

+ Q3 2013 – Q4 2014

Solar Agent-Based Model (ABM)

Agents

Autonomous decision-makers + Attributes

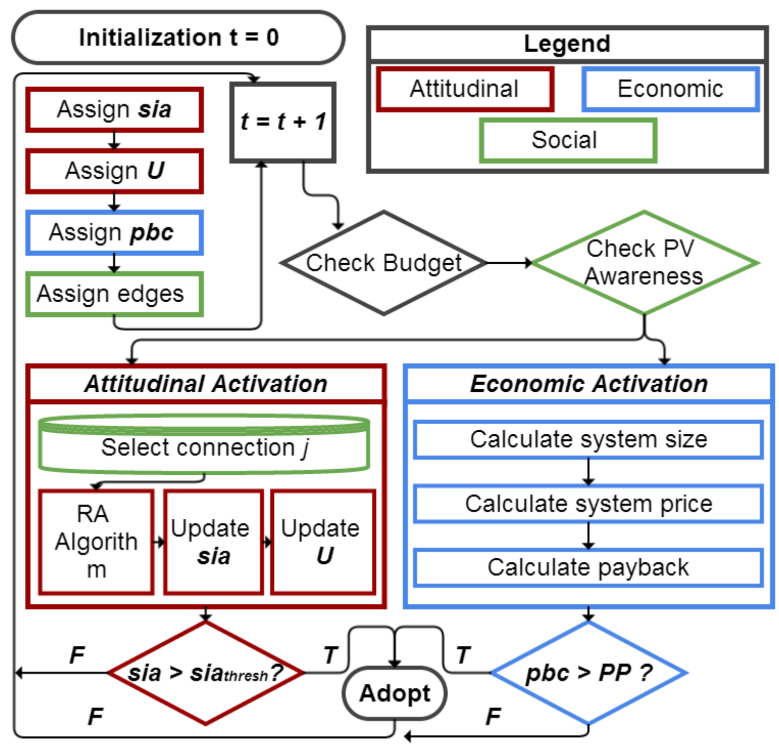


Explicitly coded composite (theoretical) decision rules:

D1) I only adopt if I *think* going solar is a good thing (**beliefs**): $Attitude_i > Global\ threshold\ (\Phi)$

D2) I only adopt if I can afford solar (**controls**): $PP_{it} < pbc_i$

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



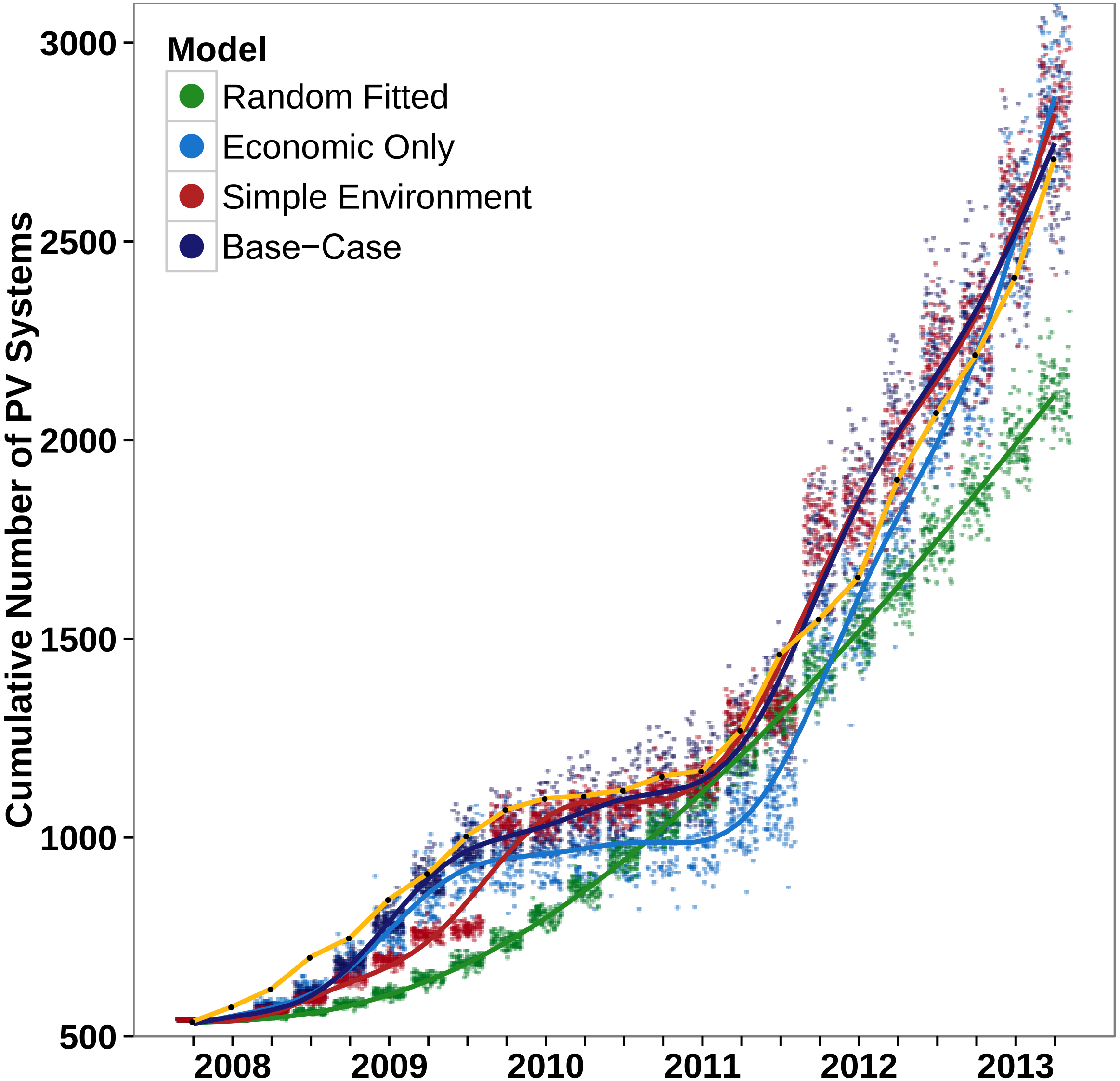
Which Model Components are Most Critical for Accuracy? Four Model Variations

Social interactions | Structure of social networks | Resolution of irradiance data

	Model Features				
Model	Initialization	Social Network	Attitudes	PV Economics	Irradiance Resolution
Base-case	Empirical	Yes (SWN)	Yes	Yes	Household
Simple Environment	Empirical	Yes (SWN)	Yes	Yes	City
Economic Only	Empirical	No	No	Yes	Household
Random Fitted	Random	Yes (ER)	Yes	Yes	None

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

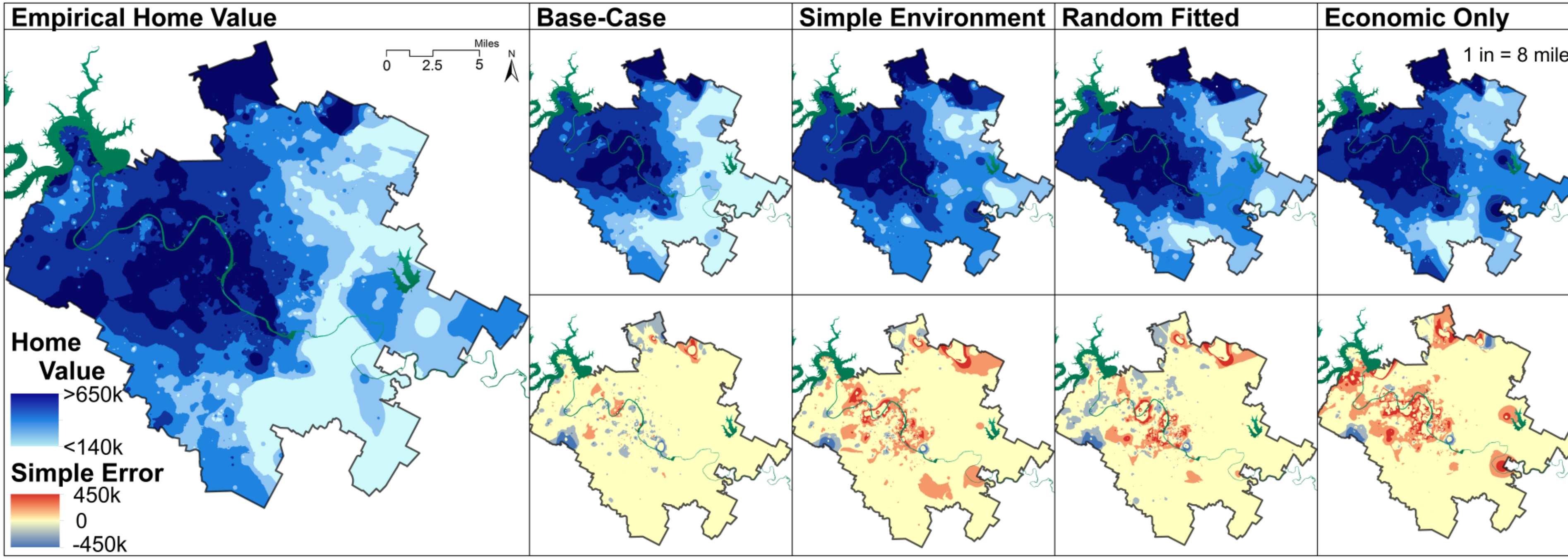


Fit to minimize cumulative

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

- **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								
Model	**RMSE marginal**	**Sp: Simple**	**Sp: Fuzzy κ**	**Sp: r^w**	**Dem: RMSE**	**Dem: Simple**	**Dem: Fuzzy κ**	**Dem: r^w**
Base-case	76.93	0.46	0.43	0.86	110,580.2	-37,967.7	0.81	0.81
Simple Environment	106.91	0.99	0.42	0.56	162,436.7	109,296.8	0.73	0.74
Random Fitted	65.95	-1.09	0.34	0.46	113,289.5	-88,463.62	0.77	0.76
Economic Only	88.60	1.37	0.41	0.55	157,047.6	147,748.8	0.74	0.74

Prediction Accuracy ~5%

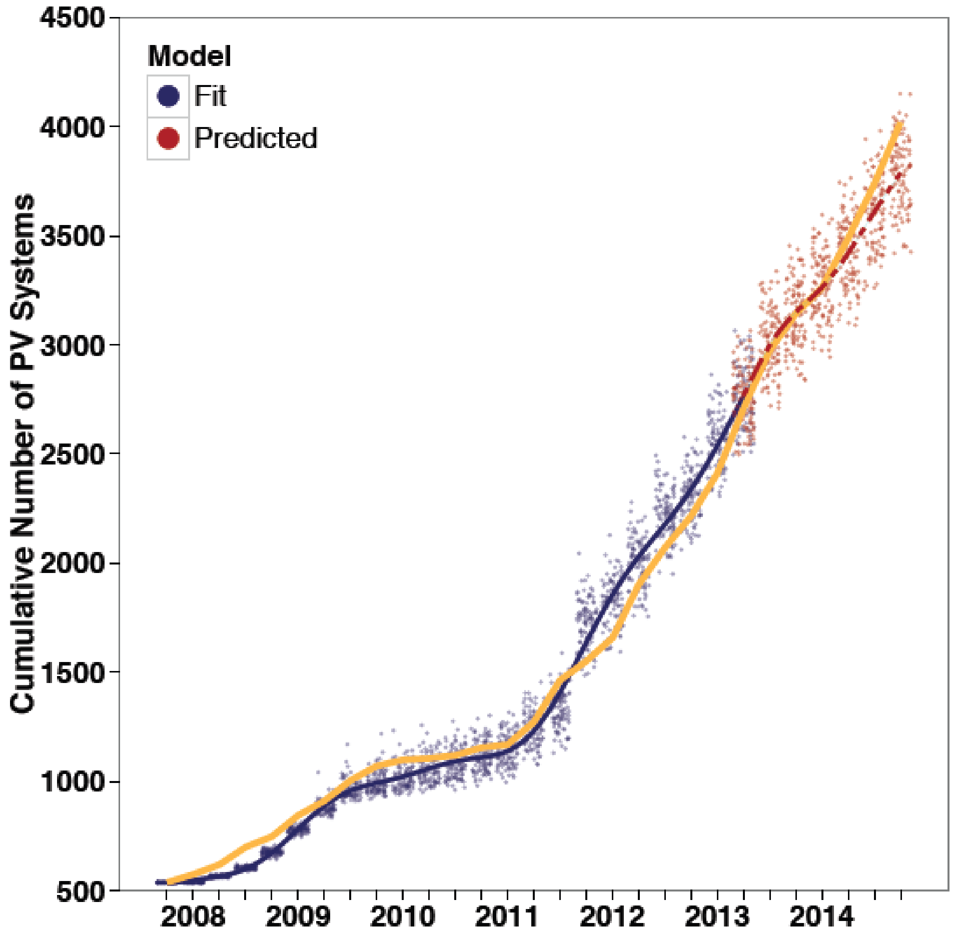
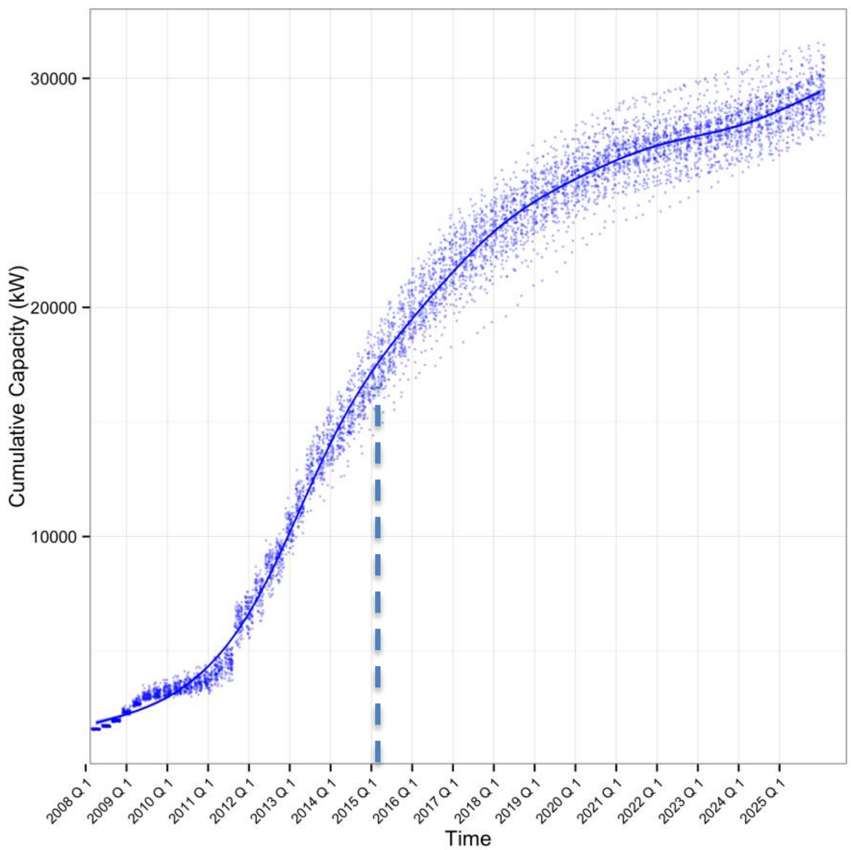
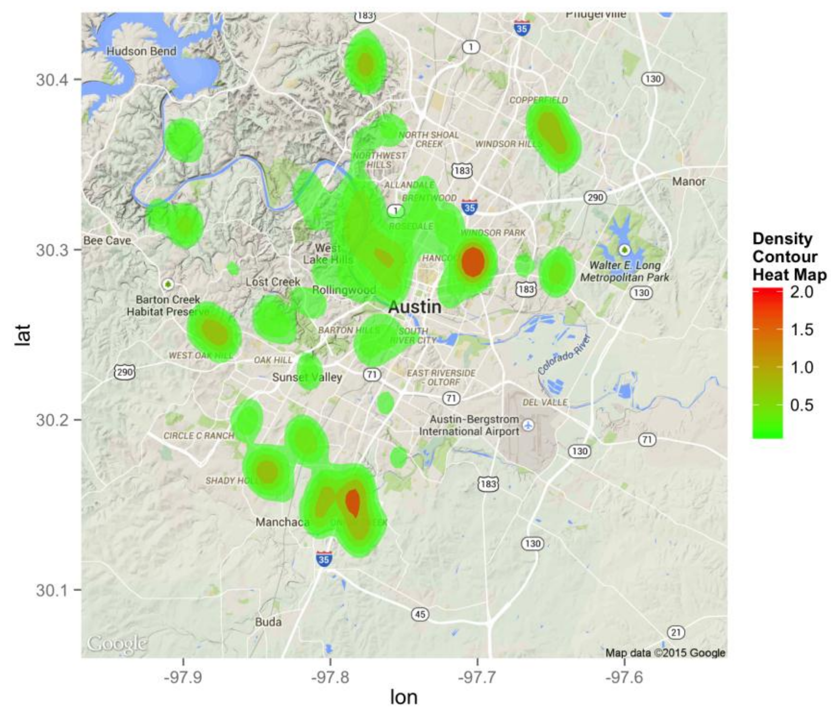


Figure 5: Fit and predicted model outcomes compared to empirical data. Observed adoption levels are shown by the gold line. The purple line shows the Integrated Model, described in Section 4.1. The average of the six quarter forecast (Q3 2013 - Q4 2014) is shown as the red dashed line (Section 4.1.1). 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)



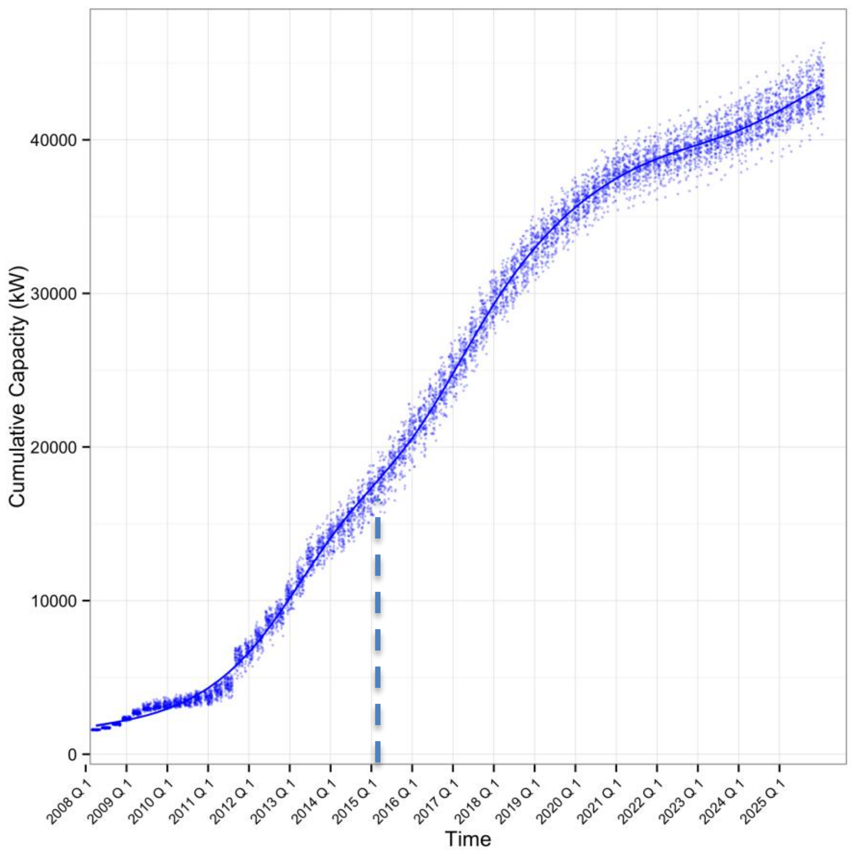


Total Capacity 2020: 26,623 kW
Total Capacity 2025: 29,418 kW

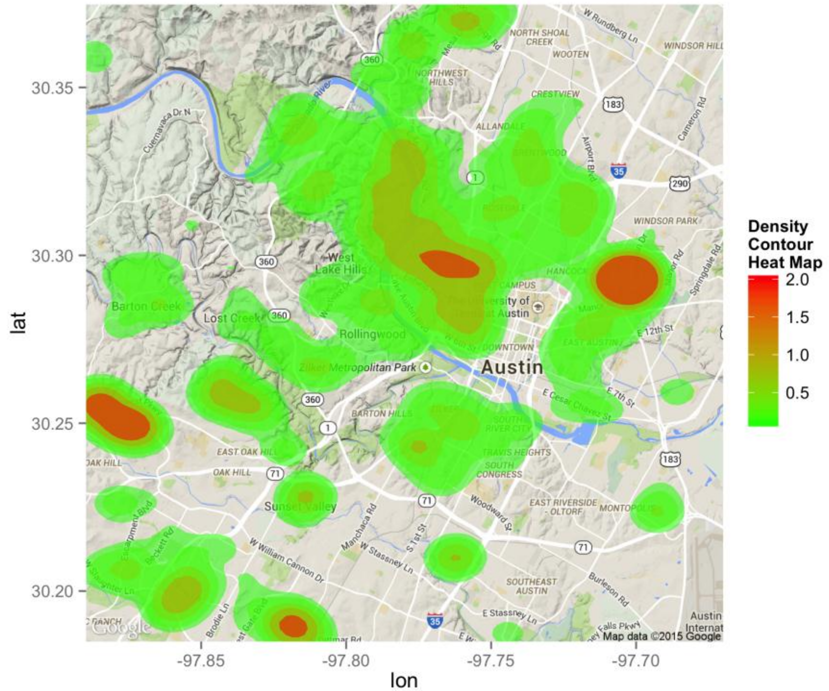
Total Adoptions 2020: 5,147
Total Adoptions 2025: 5,452

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

Predicted Capacity and Spatial Density of Residential Solar PV Adoption in Austin by 2025 (Scenario: Optimistic)



CAGR ~15% across a range of scenarios

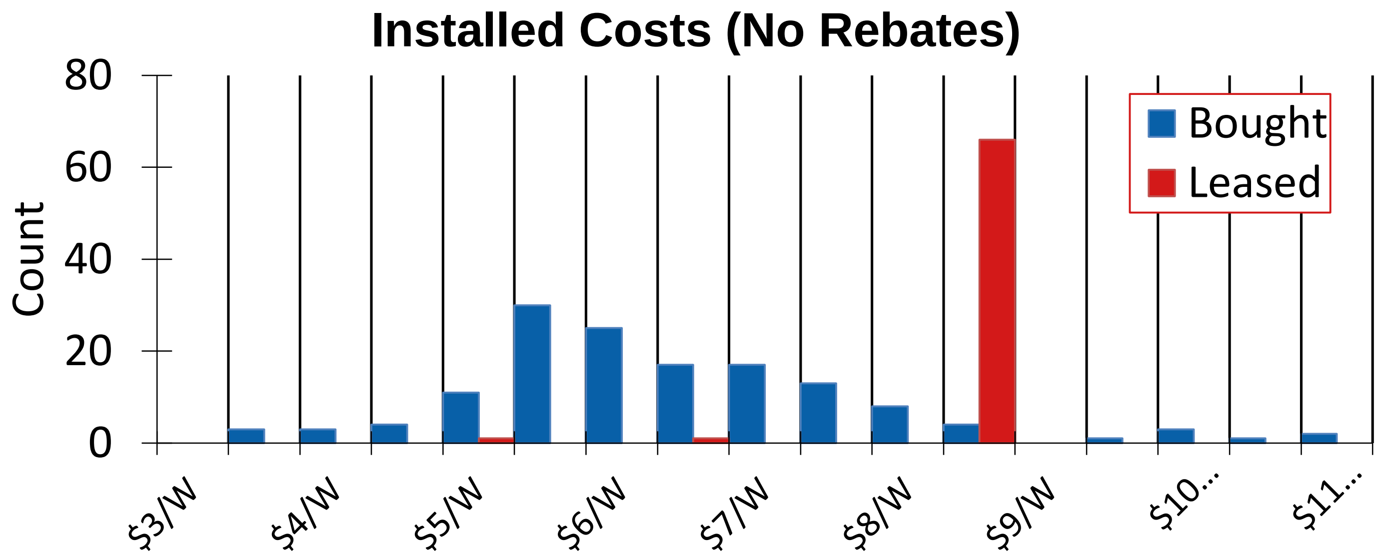


Total Capacity 2020: 37,836 kW
Total Capacity 2025: 43,436 kW

Total Adoptions 2020: 6,705
Total Adoptions 2025: 7,330

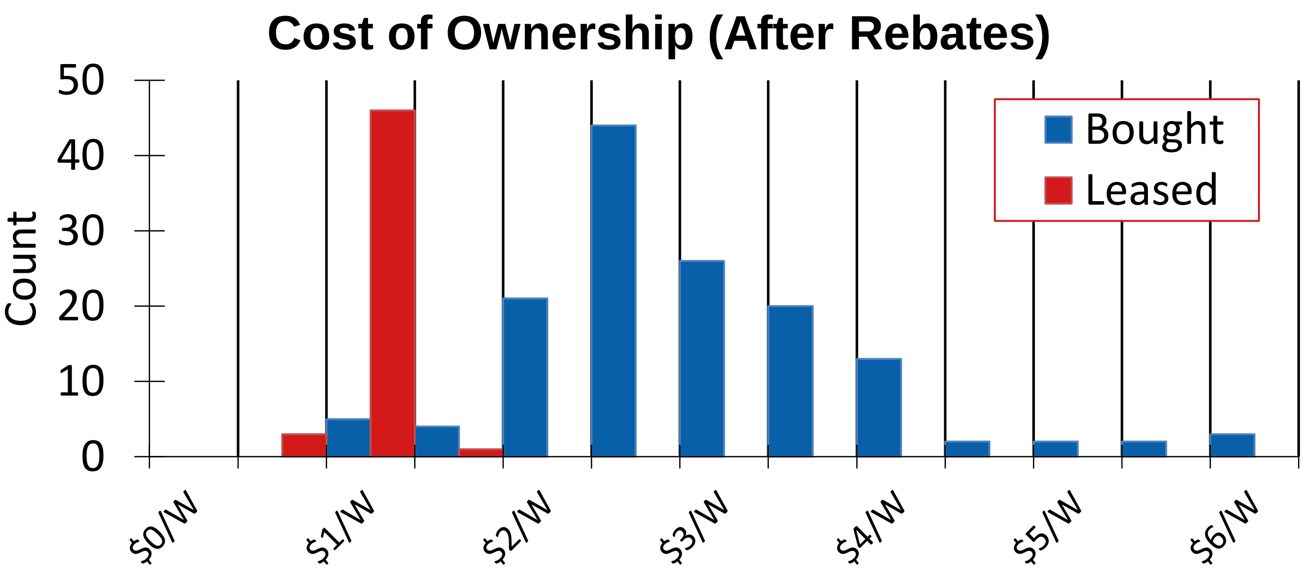
Model 1712 parameters: FITC stays at 0.30, VoS 11.3c/kW, Rebates decline by 20% annually ending 12/2020, Installed costs decline by 10% in 2015 & 2016, by 4% otherwise1

Installed Cost vs. Cost of Ownership



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

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



Buyers:
Mean: $2.6/W
SD: $0.95/W

Leasees:
Mean: $0.70/W
SD: $0.13/W

Source: Rai & Sigrin, “Diffusion of environmentally-friendly energy technologies: buy versus lease differences in residential PV markets,” *Environmental Research Letters,* 8(1), 014022 (2013).

Non-Adopter Survey (Aug-Sep 2014) – Overall Conclusion

- **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

“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

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- **Austin Energy**
- **Texas Advanced Computing Center (TACC)**

References

- Two ABM papers on the predictive modeling of solar diffusion are available at:
- Robinson, S.A. and Rai, V. (2014). Determinants of Spatio-Temporal Patterns of Energy Technology Adoption: An Agent-Based Modeling Approach.
  - 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.
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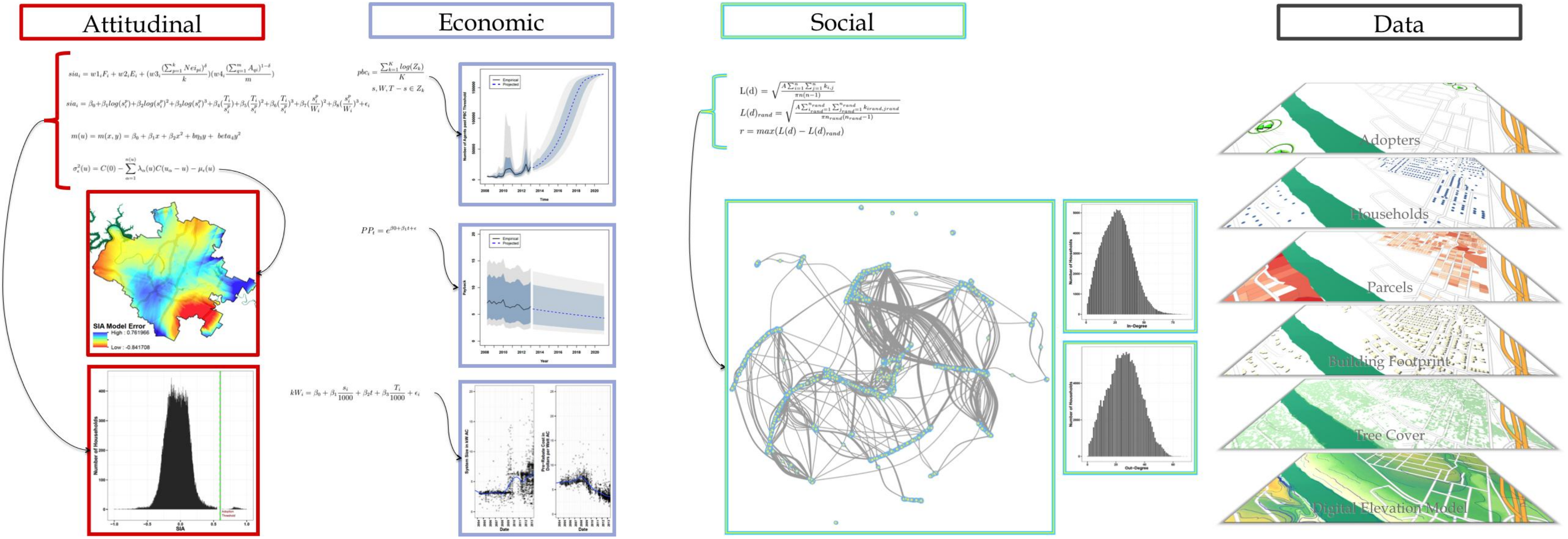
- Blackburn, G., Magee, C., and Rai, V. Solar Valuation and the Modern Utility's Expansion into Distributed Generation, *The Electricity Journal*, 26(11), 18-32, 2014.
- Rai, V. and Sigrin, B. Diffusion of Environmentally-friendly Energy Technologies: Buy vs. Lease Differences in Residential PV Markets, *Environmental Research Letters*, 8(1), 014022 (1-8), 2013.

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)**

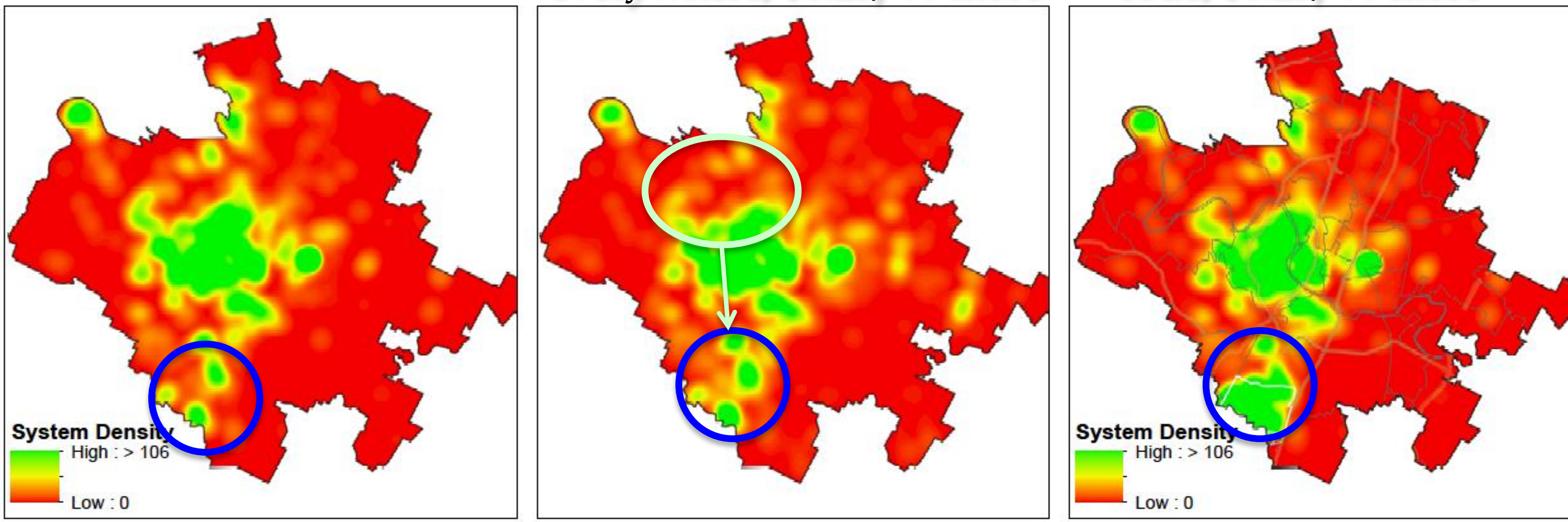
Multiple, Matched Datasets

Data Sources					
Source	**Content**	**Scope**	**Scale**	**Resolution**	**Time frame**
Austin Energy	System details, location, installation date, etc	PV Adopters	Population	Household	2004-2013
UT Austin	Survey responses regarding installation decision	PV Adopters	Sample, 22.5%	Household	2011-2014
TCAD	Home value, parcel size, land use code, etc	Land parcels	Population	Household	2013
CAPCOG	LIDAR images	City of Austin visible above ground	Population	6in	2013
USGS	National Elevation Dataset	City of Austin elevation ASL	Population	3m	2013

Application: Scenario, Tiered Rebates

Lower income quartile, everywhere, $0.25/W more

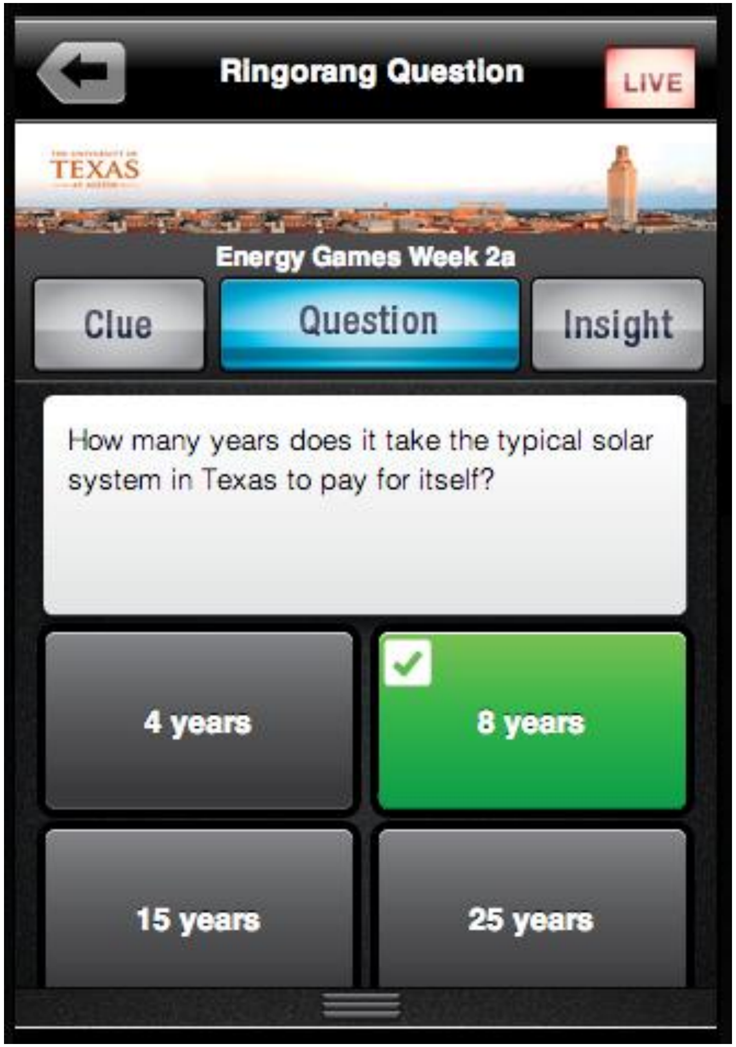
Everyone in a target zip code, $0.25/W more



(a) Base-case (b) Batch 327 (c) Batch 328

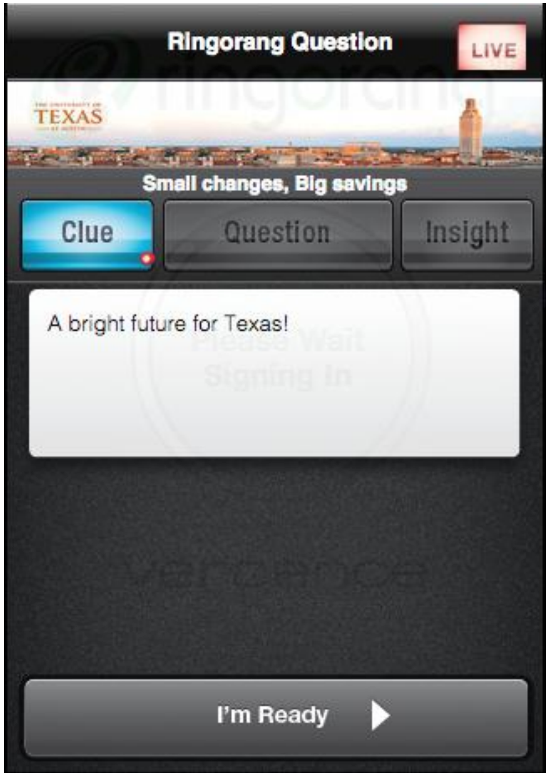
Localized adoption increases from <1% in base-case to ~11% in Sc.328

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

< 1min

- 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