Social-Psychological Analysis of Demand Response Behaviors and Home Energy Management System

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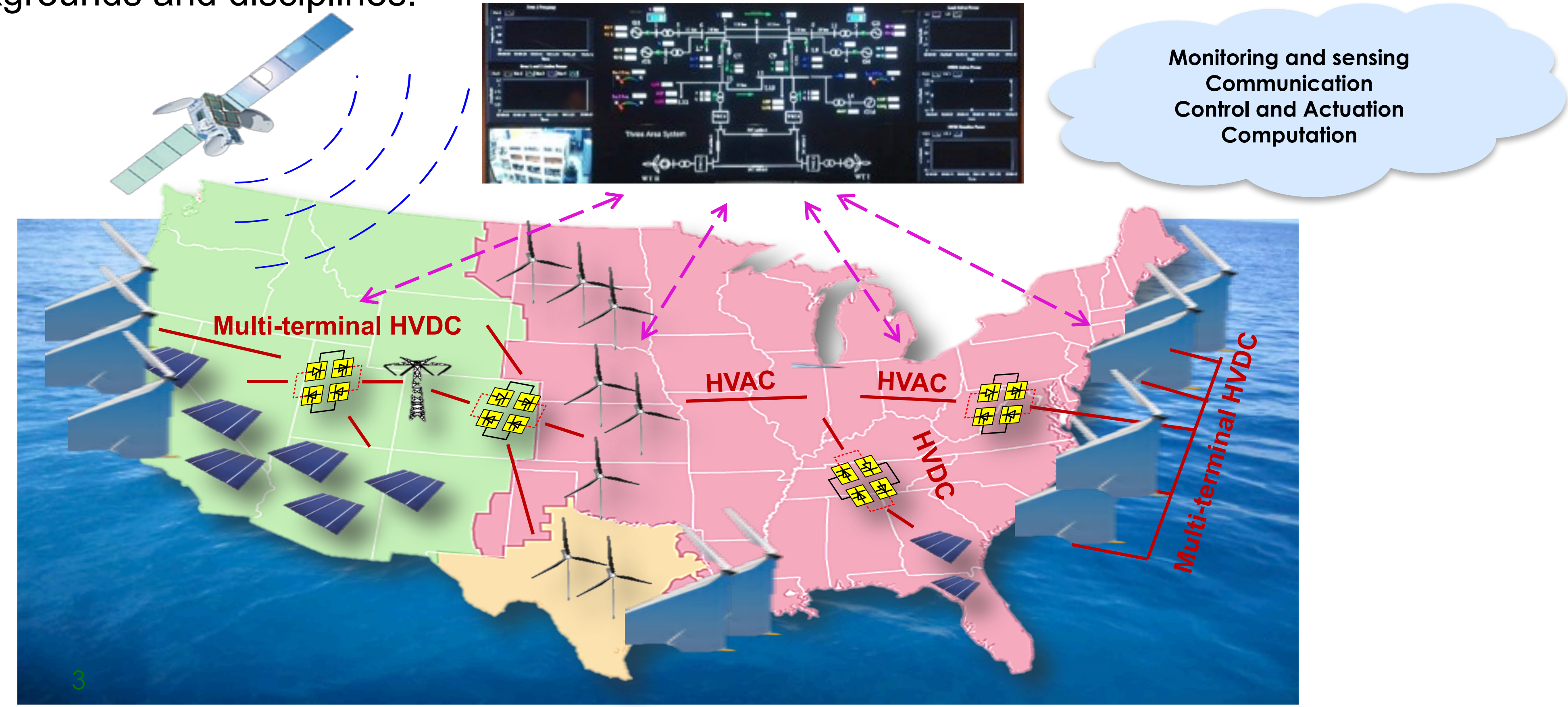
CURENT – An NSF/DOE ERC

- Selected by National Science Foundation (NSF) and Department of Energy (DOE) from a few hundred proposals across all engineering disciplines.
- Base budget: ~$4M/year for up to 10 years. Other funding: $2-3M/year
- First and only ERC devoted to power grid (transmission).
- Four universities in the US (UTK, RPI, NE, TU)
- Industry partnership program (36 members as of 2017)
- 18 patent applications and 35 invention disclosures (since inception)
- Center began Aug. 15th 2011. Funding reviewed every year.
- CURENT Students: 154 graduate and >80 undergraduate

CURENT Vision

- A nation-wide transmission grid that is fully monitored and dynamically controlled for high efficiency, high reliability, low cost, better accommodation of renewable sources, full utilization of storage, and responsive load.
- A new generation of electric power and energy systems engineering leaders with a global perspective coming from diverse backgrounds and disciplines.



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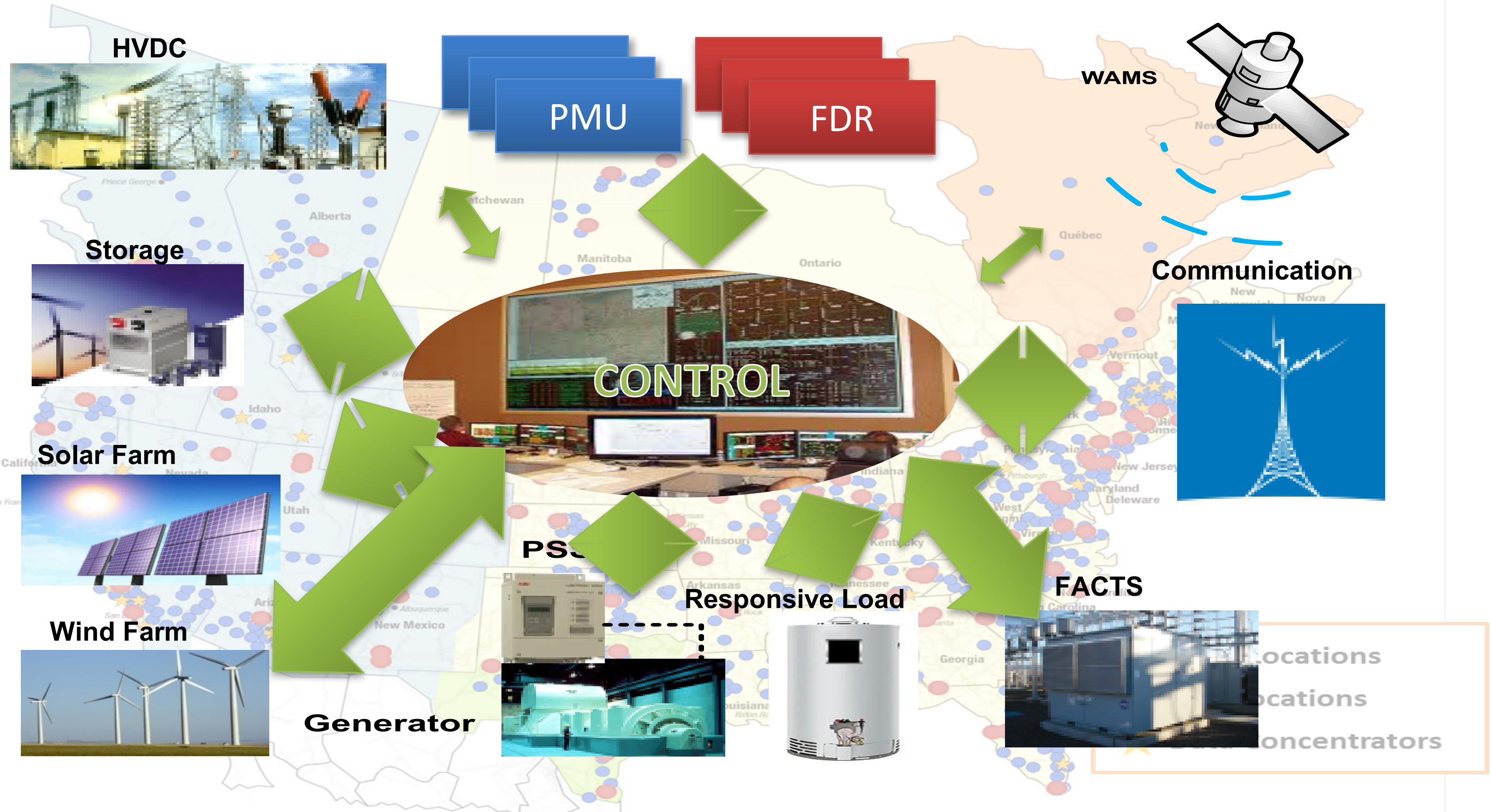
What is CURENT?

Wide Area Control of Power Grid

Measurement &Monitoring

Communication

Actuation



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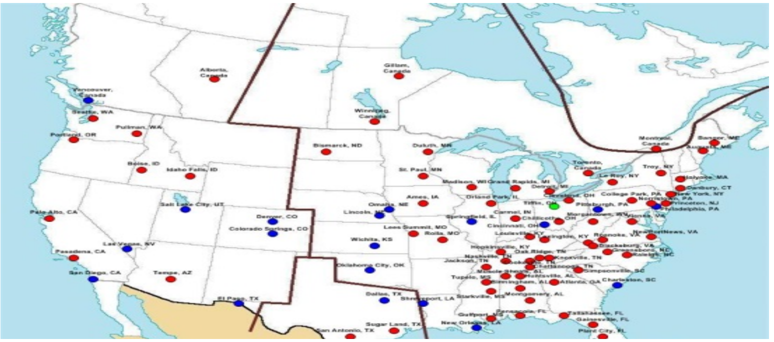
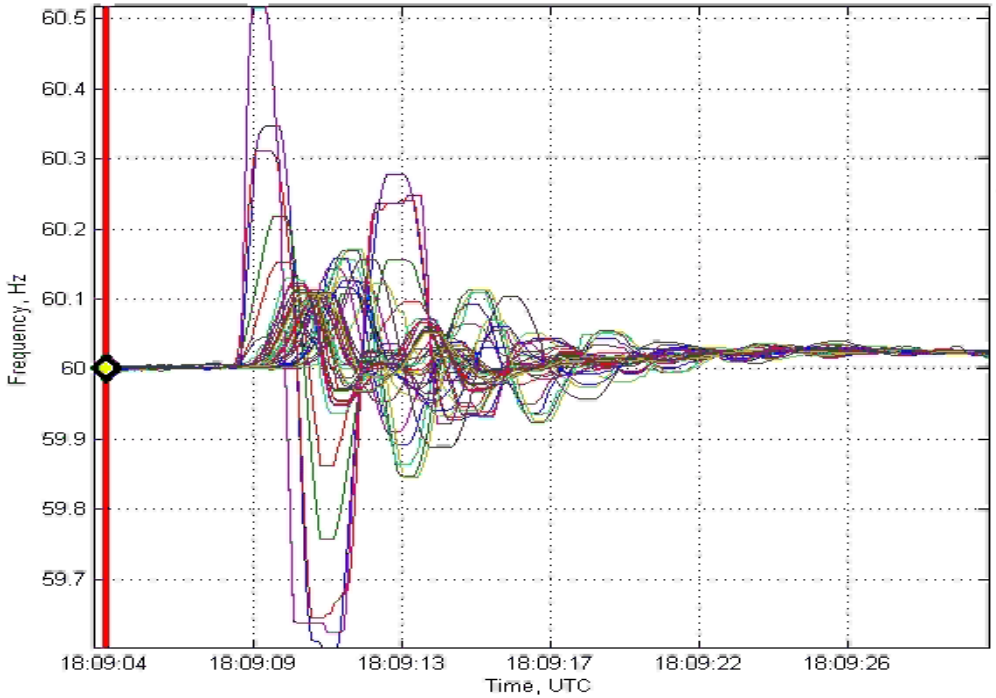
Wide Area Measurement

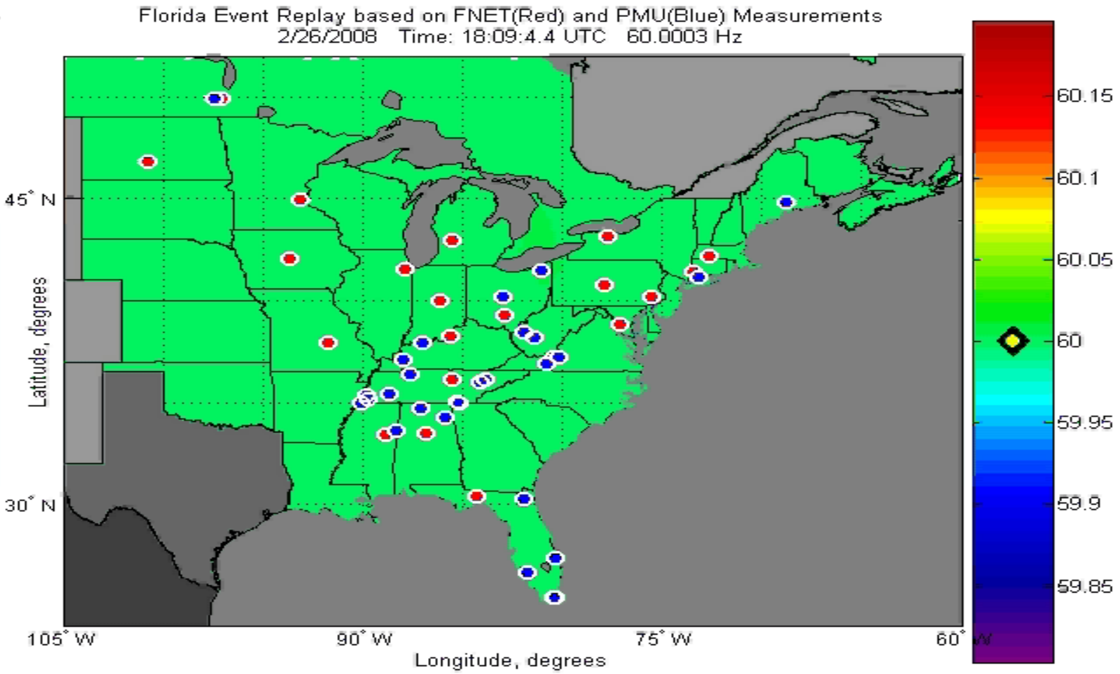
Unique Capabilities: UWA real-time grid monitoring system at UTK – Dr. Yilu Liu

FDR Sensor



FNET Monitors in the Field





Three-plane Diagram

Engineered Systems

Testbeds

- Hardware Testbed
- Large Scale Testbed

Barriers
- System complexity
- Model validity
- Multi-scale
- Inter-operability

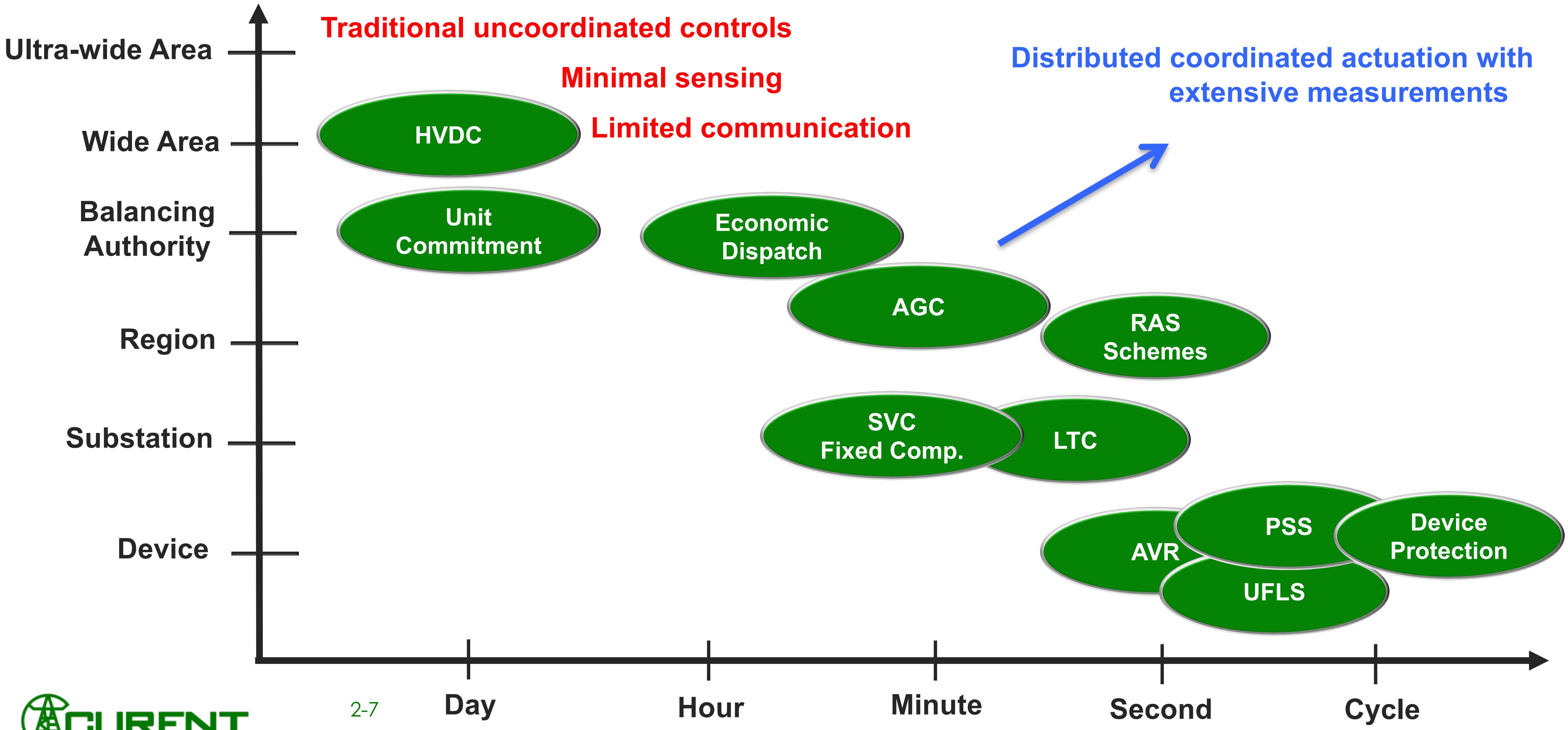
Enabling Technologies / Fundamental Knowledge

	Monitoring	Modeling	Control	Actuation
Enabling Technologies	Situational Awareness & Visualization	Estimation Communication& Cyber-security	Control Design & Implementation	System-level Actuation Functions
Fundamental Knowledge	Wide-area Measurements	Modeling Methodology	Control Architecture Economics & Social Impact	Actuator & Transmission Architecture

Barriers
- Poor measurement design
- Cyber security
- Actuation & control limitation

- *Barriers*
- Lack of wide-area control schemes
- Measurement latency
- Inflexible transmission systems

Today's Operations
Some Wide Area and Some Fast but not Both



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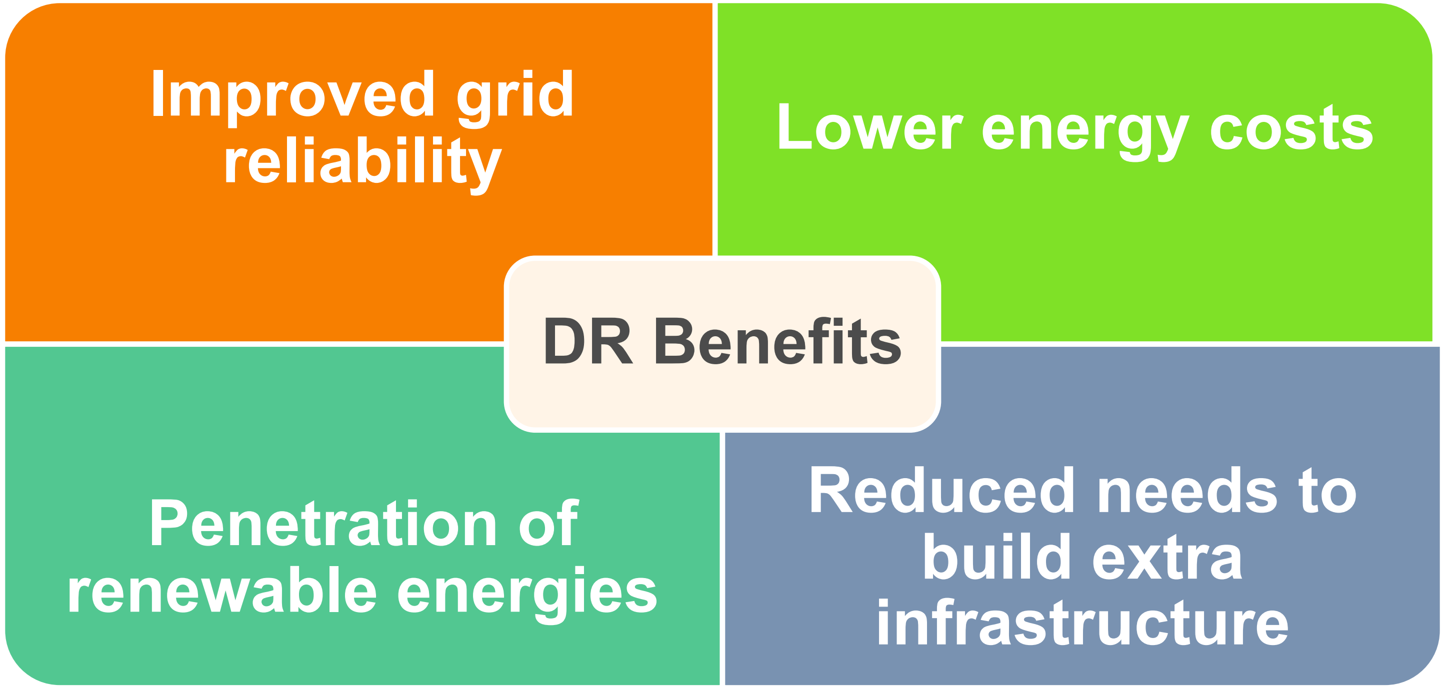
Goals of Promoting Demand Response (DR)

DR programs are designed to encourage customers to reduce or shift electricity usage during peak hours in response to time-based rates or other forms of financial incentives.



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Purposes of Our Study

- Traditional approach to promoting DR programs based on price and rational choice modeling: peak & off-peak pricing, dynamic pricing, additional financial incentives, etc.

- **Our Research Questions:**

1) How do demographics, and social-psychological factors and energy use habits influence DR acceptance?
2) To what extent do financial incentives or behavioral nudges (non-financial incentives, override) help customers accept DR programs?
3) Will the effect being same for everyone?

DR Acceptance with Social-psychological Focus

Goals: a) To investigate the influence of financial incentives and behavioral nudge (override, control) on DR acceptance, across different types of residents and income levels

- Installing an automatic switch to re-schedule A/C cycling – direct load control
- Installing an automatic thermostat controller to tweak A/C settings - direct load control
- Responding to DR alerts by adjusting A/C settings – voluntary behavior
- Voluntarily reducing A/C use during peak hours – voluntary behavior

b) To explore how **demographics** and **social-psychological factors** affect DR acceptance based on representative samples

- Demographics: age, ethnicity, education
- Household characteristics: homeownership, household size
- Social-psychological factors: environmental and cost concerns, attitudes, social norms, Perceived behavioral control, trust in the utility company

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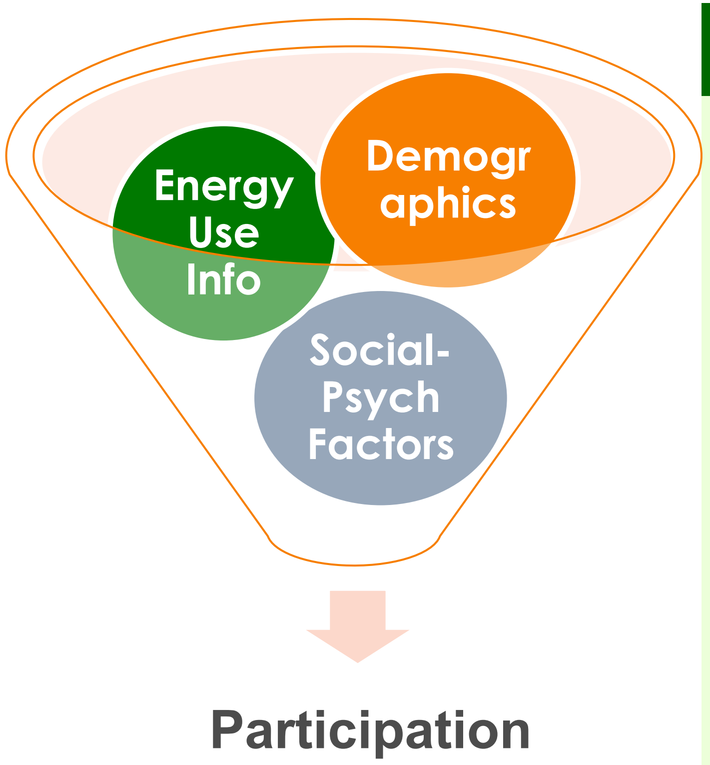
Example of Predictors of HAVC-related DR Behaviors



Energy Use Info	Demographics	Social-Psychological
Monthly Bill_Average	Age	Energy Concern
Stay Home (9am-5pm)	Gender	Bill Consciousness
Light Use	Income	Frugality
Computer Sleep Mode	Education	Need for Comfort
Thermostat Settings	Political Orientation	Need for Convenience
Night Adjustments	House Sqft	Need for Control
	Household Size	Trust
	Weather Region	Subjective Norm
		Perceived Control

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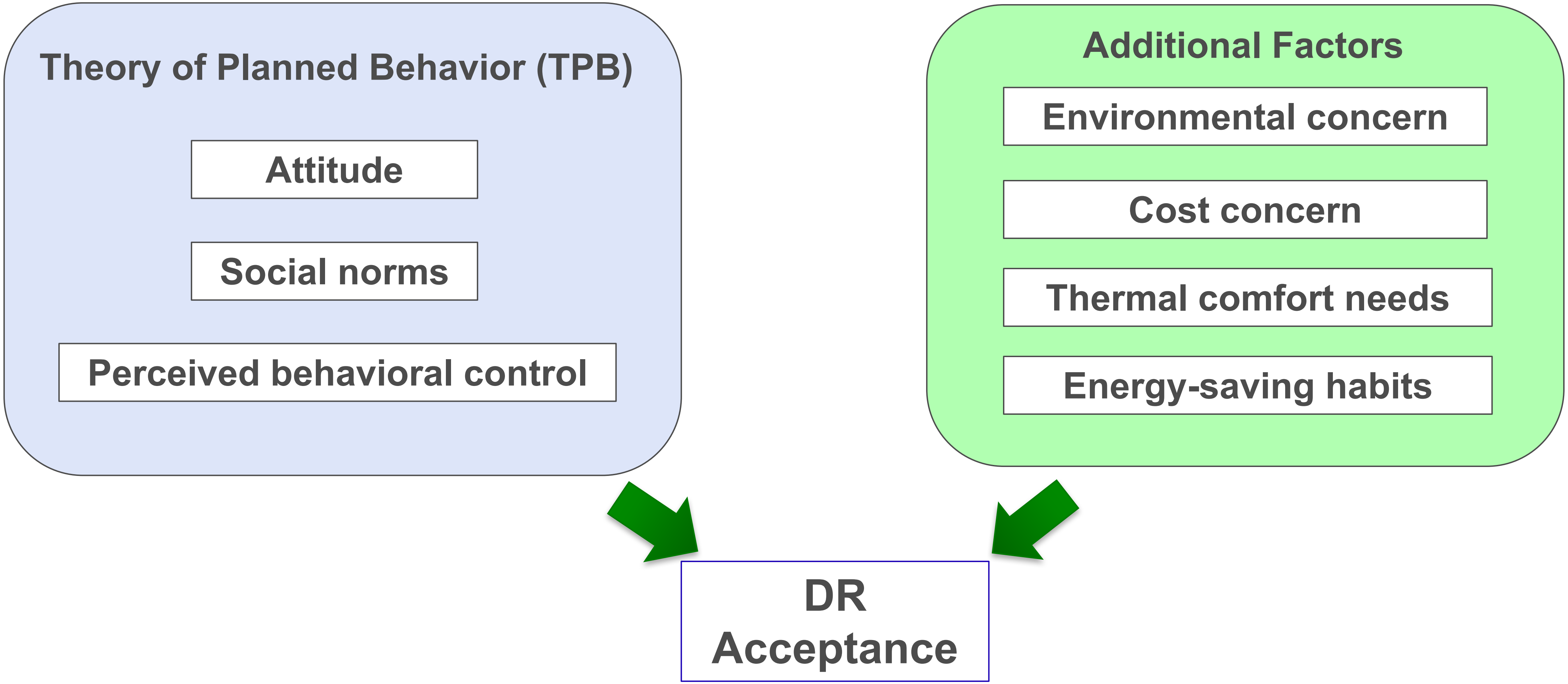
Theoretical Framework – An Extended TPB Model

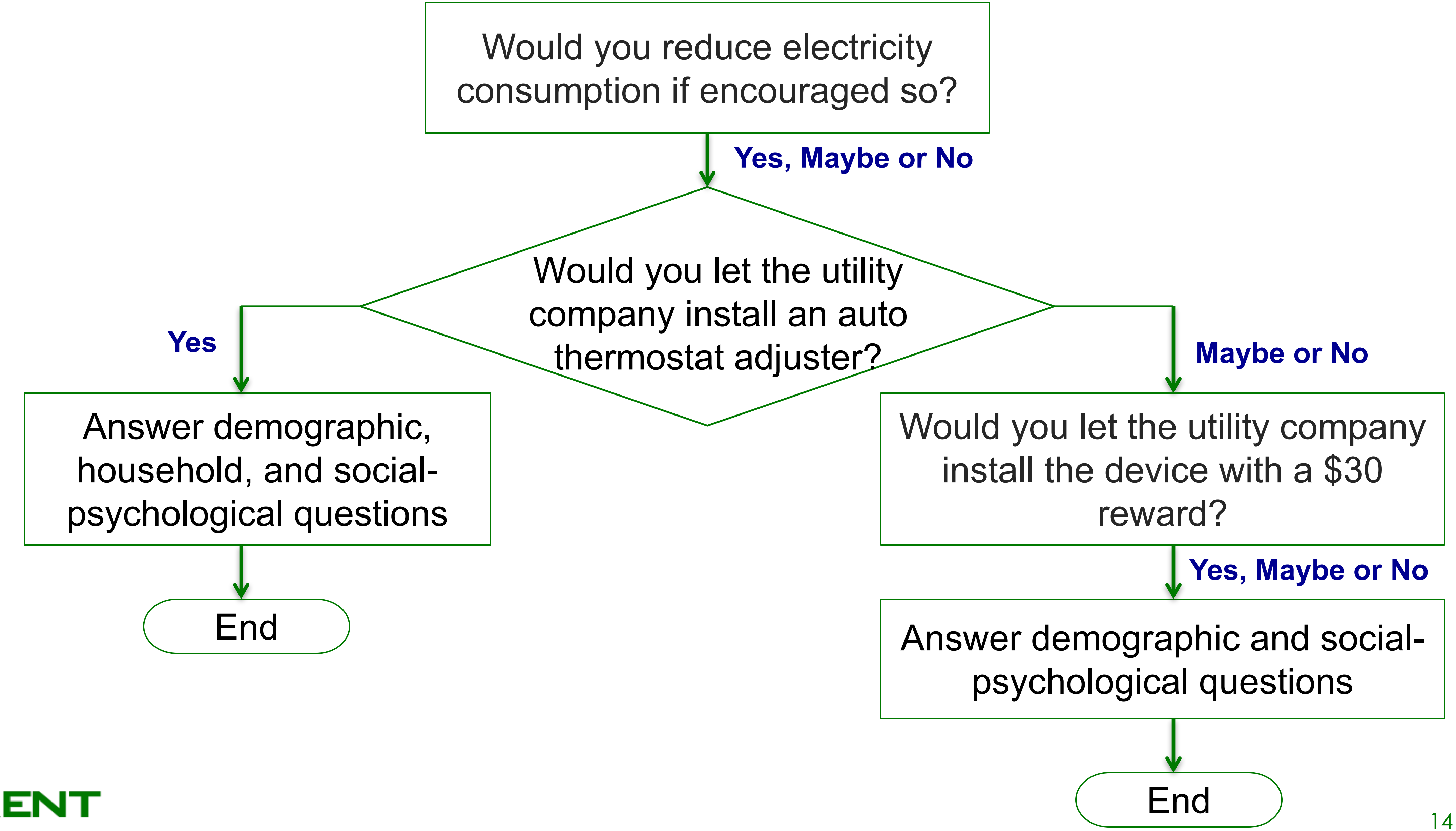


Procedures of Data Collection

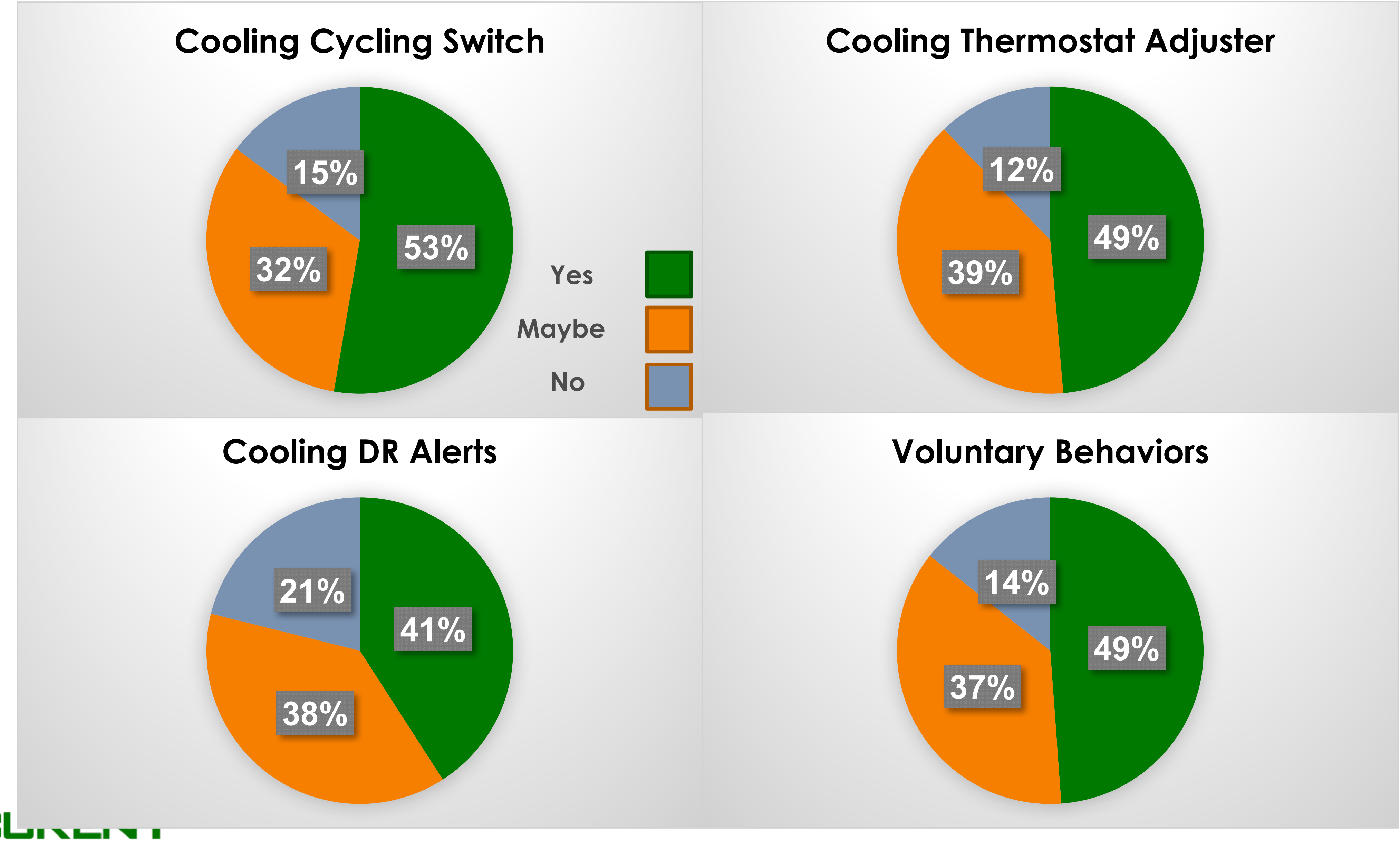
- Online survey: sampling representation in gender, income, and ethnicity based on state's census.
- 1482 valid responses from residents in CA, TN, TX, & VA
  - 359 LIHs, 725 MIHs, 398 HIHs
  - Use electricity for cooling
  - Pay non-flat-rate electricity bills

- 18 to 71 years old (*Mean* = 41.07, *SD* = 13.48)

Example of Survey Structure



Acceptance Rate of DR Programs/Behaviors



Five Types of Residents

1. **Early acceptors:** accepted without any conditions
2. **Non-distinguishing convertors:** accepted when both $30 incentive and override option were provided
3. **Money-motivated convertors:** accepted only with $30 incentive
4. **Control-motivated convertors:** accepted only with the override option
5. **Straight non-acceptors:** would not accept anyway

Financial Incentives vs. Behavioral Nudge (Override)

Main Findings:

1. About 50% participants were willing to accept DR without any incentives or conditions
2. More participants accept DR for override (yellow) than for the financial incentive ($30) (gray).

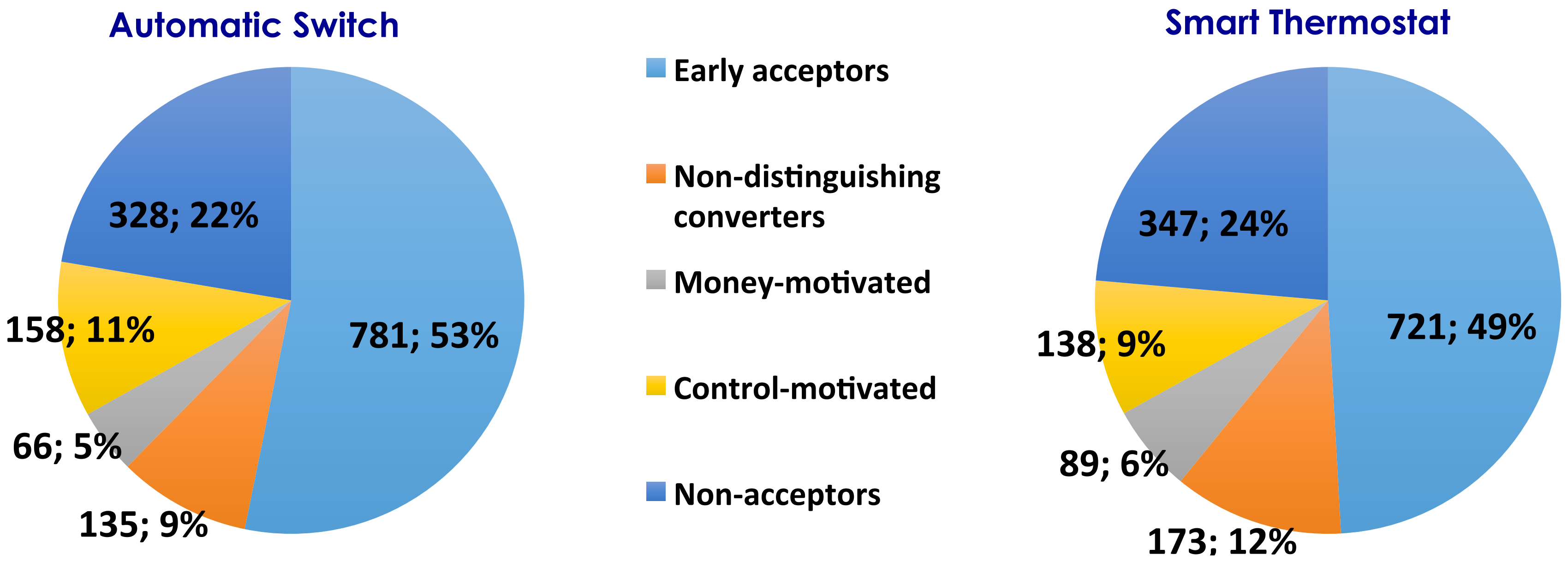
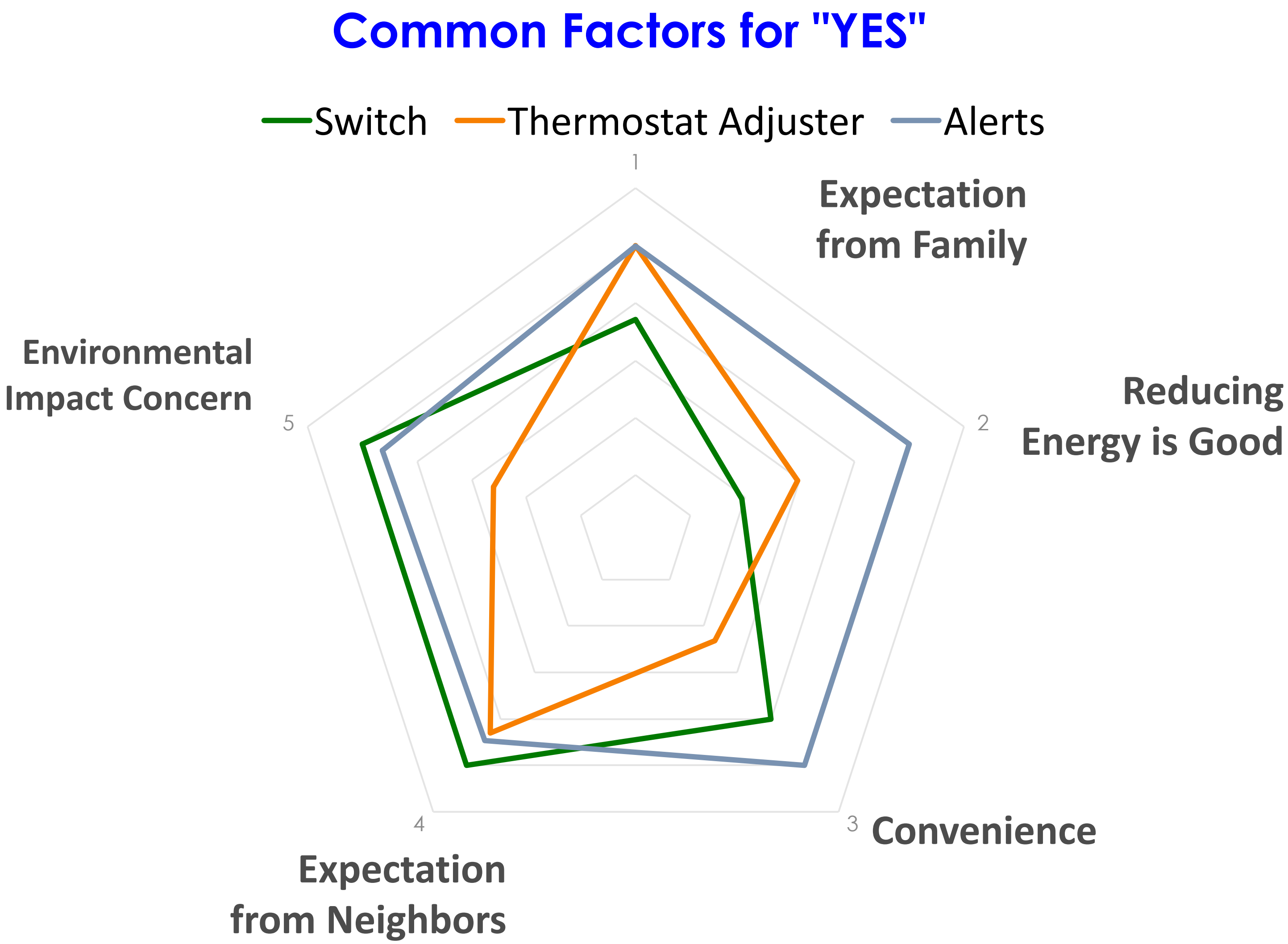


Fig. DR acceptance with and without nudges and incentives

Interesting Observation – Common Factors (TOP 5s)



- Expectation from family and neighbors are influential.
- People, who feel it’s convenient to reduce energy use, prefer switch and alerts.
- People choosing auto thermostat adjuster is less concerned about the environment.

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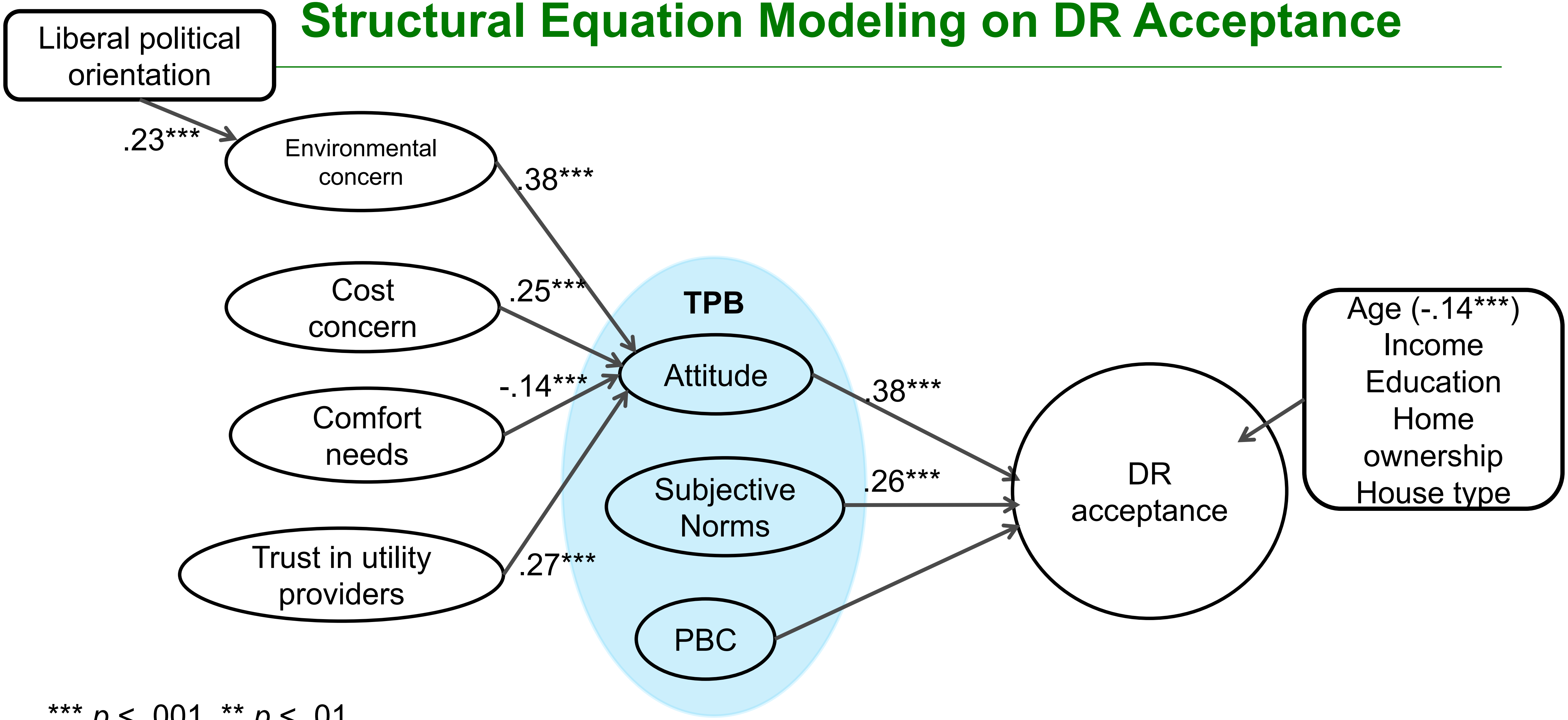
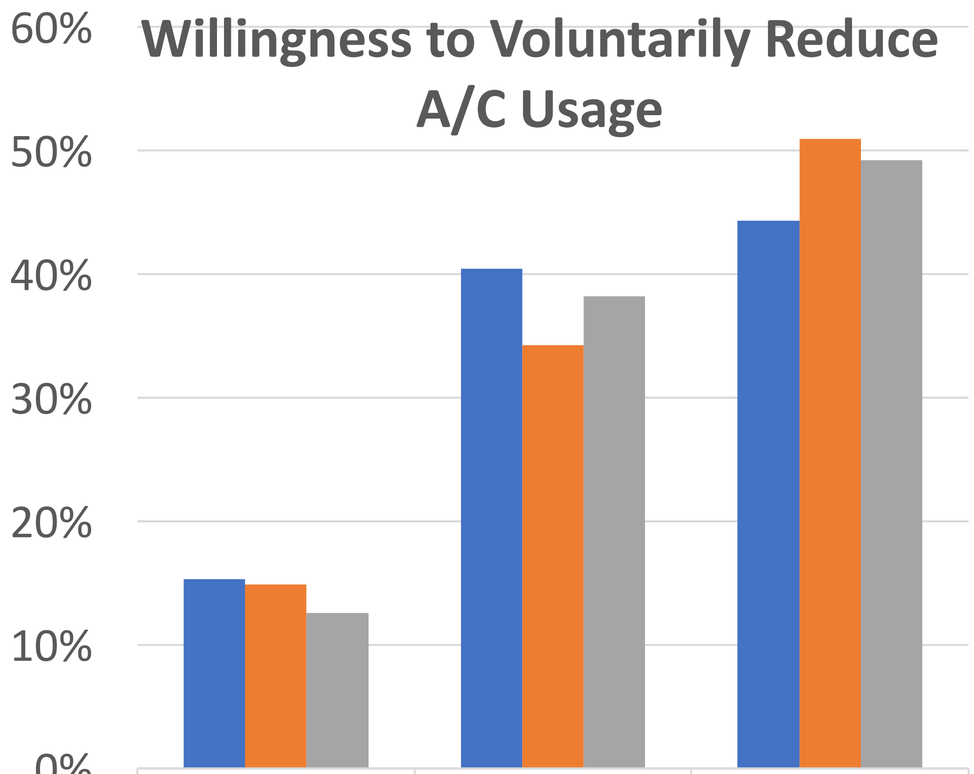
Structural Equation Modeling on DR Acceptance



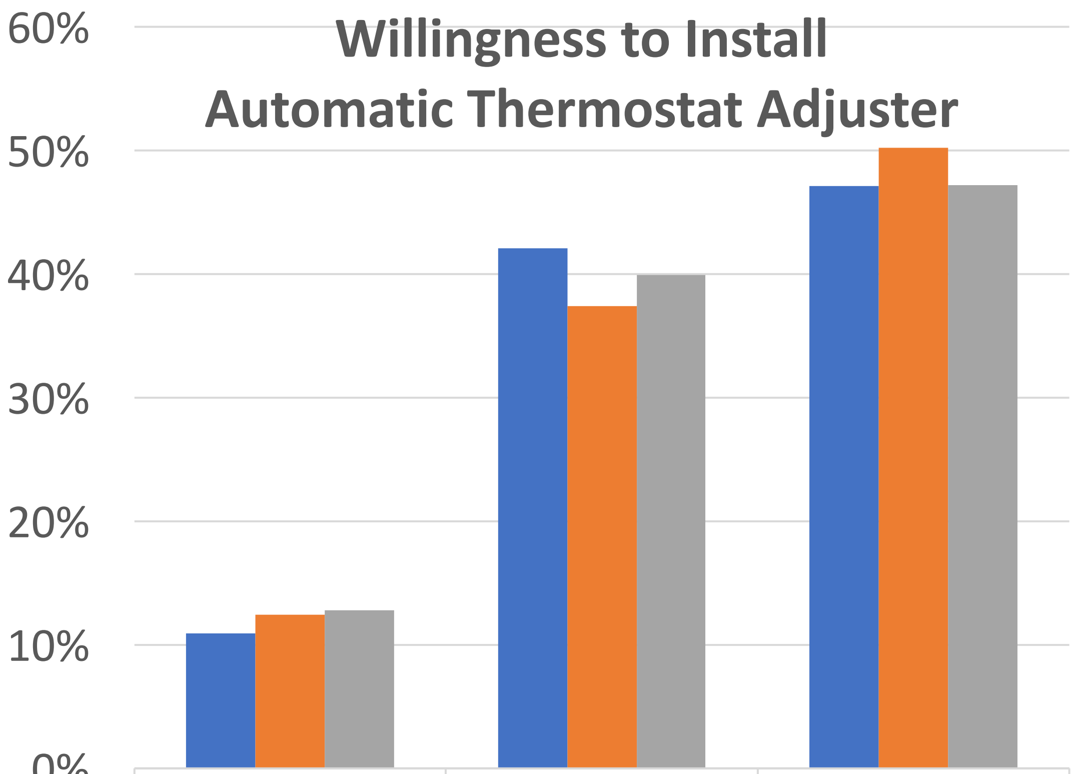
*** $p < .001$, ** $p < .01$

† Programs include: 1) installation of utility-controllable A/C cycling switch, 2) installation of utility-controllable A/C thermostat adjuster, and 3) responding to peak-hour alerts by shutting down or adjusting A/C settings.

Voluntarily Reduce A/C Usage vs. Direct Load Control



	No	Maybe	Yes
LIHs	15.30%	40.40%	44.30%
MIHs	14.90%	34.20%	50.90%
HIHs	12.60%	38.20%	49.20%



	No	Maybe	Yes
LIHs	10.90%	42.10%	47.10%
MIHs	12.40%	37.40%	50.20%
HIHs	12.80%	39.90%	47.20%

No statistically significant difference across income levels on either DR behavior

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DR Acceptance among Three Income Levels

On voluntarily raising A/C thermostat settings by 2-3℉ during peak hours in summer

Low-Income

- Lower education
- Lower social norms
- Lower perceived behavioral control

	Yes	Maybe	No
Low-Income	44.3%	40.4%	15.3%
Mid-Income	50.9%	34.2%	14.9%
High-Income	49.2%	38.2%	12.6%

Not significantly different

Mid-Income

Higher privacy concern
Better energy-saving habits

High-Income

- Higher education
- Older
- Bigger home
- Lower concern for energy cost

Regression Result on Voluntary Peak Reduction

Variables	LIHs		MIHs		HIHs	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Age	-0.01	0.99	-0.01	0.99	-0.02	0.98
Ethnicity	-0.12	0.88	**0.39***	1.47	-0.12	0.89
Education	0.09	1.09	-0.06	0.94	0.12	1.13
Homeownership	-0.40	0.67	0.23	1.02	-0.22	0.81
Household size	-0.04	0.96	0.00	1.00	-0.15	0.87
Attitude	**0.82*****	2.30	**0.44****	1.55	**0.57****	1.77
Norms	**0.45****	1.56	**0.45*****	1.55	0.20	1.22
PBC	**0.31***	1.36	0.04	1.04	-0.14	0.87
Environmental concern	-0.02	1.00	0.08	1.09	**0.28***	1.33
Bill concern	-0.06	0.94	0.18	1.20	0.32	1.37
Thermal comfort	**-0.37****	0.69	**-0.49*****	0.61	**-0.41****	0.66
Energy habits	0.12	1.12	**0.56*****	1.76	**0.64****	1.89
R^2	0.28		0.27		0.31	
Correct classification percentage	69.38		70.95		69.11	

Regression Result on Installing Automatic Thermostat Adjuster

Variables	LIHs		MIHs		HIHs	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Age	**-0.03****	0.97	-0.02**	0.98	**-0.03****	0.97
Ethnicity	-0.13	0.88	**0.36***	1.44	0.34	1.40
Education	0.06	1.06	0.04	1.04	**0.29***	1.33
Homeownership	**-0.52***	0.60	-0.16	0.86	-0.46	0.63
Household size	0.07	1.07	0.06	1.06	0.11	1.11
Attitude	**0.52****	1.69	**0.33****	1.39	**0.48***	1.61
Norms	**0.44****	1.56	**0.43*****	1.53	**0.35***	1.41
PBC	0.03	1.03	0.03	1.03	0.03	1.02
Environmental concern	**0.39***	1.48	0.13	1.14	-0.05	0.95
Bill concern	0.09	1.10	0.22	1.25	0.21	1.24
Thermal comfort	-0.13	0.88	**-0.32***	0.81	0.01	1.01
Energy habits	-0.05	0.95	0.12	1.12	**0.33***	1.39
R^2	0.25		0.19		0.24	
Correct classification percentage	69.94		65.42		69.85	

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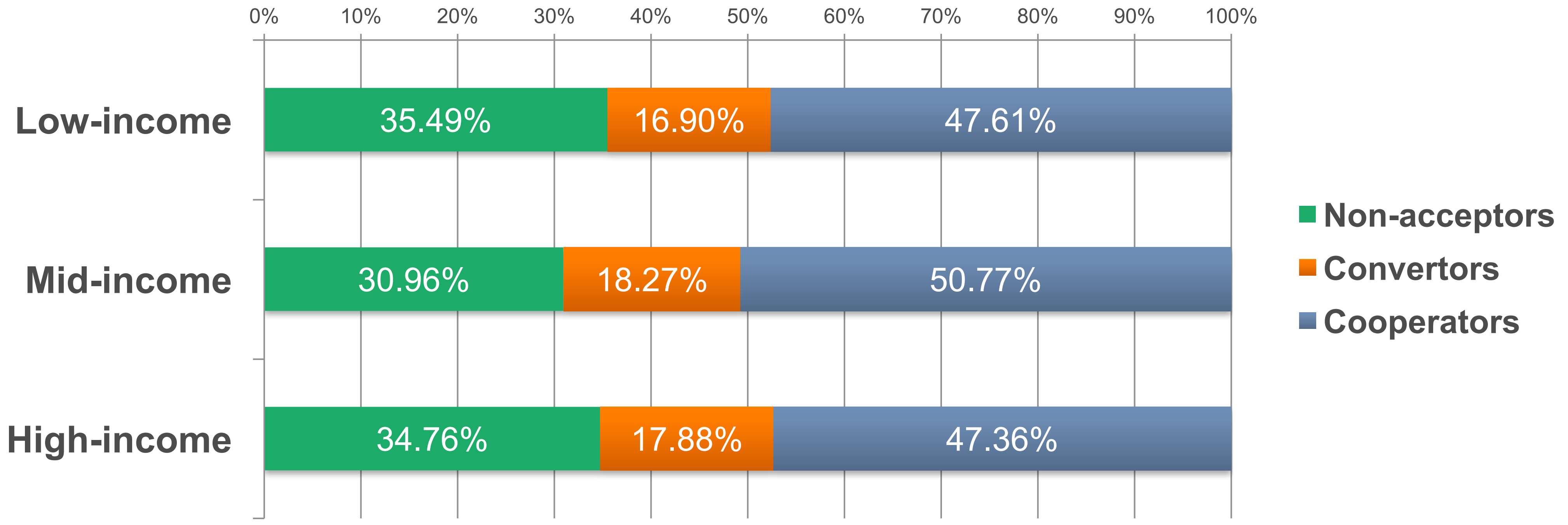
Responses to Financial Incentives

Three types of residents: non-acceptors (rejection), convertors (accepted only due to incentives), cooperators (without incentives)

RQ: Did low-income people respond to $30 incentive more than others did?



Low-income residents did NOT convert more than other groups.

Findings

- Logistic regressions conducted in the three groups suggest:
  - **Attitude and social norms** (i.e., family and friends' expectations) were positive predictors of DR acceptance in every condition.
  - **Comfort needs** was negatively associated with willingness to voluntarily adjust A/C, while **age** was mostly negatively associated with willingness to install the automatic thermostat adjuster.
  - Interestingly, **environmental concern** was a positive predictor of voluntary DR among high-income residents and a positive predictor of installation of an auto-adjuster in low-income residents.
  - **Energy-saving habit** was somewhat a positive predictor of DR acceptance among mid- and high-income residents, but not among low-income residents.

Findings

- Against common beliefs about low-income households:
  - Low-income residents did not have significantly higher cost concerns than mid-income residents in energy consumption; high-income residents did have lower cost concerns than the other two groups though.
  - Three income groups responded to the $30 incentive at similar extent; low-income residents did NOT convert from non-acceptors to acceptors because of financial incentives more than the other groups did.
  - Three income groups had similar levels of environmental concerns.

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Implications

- Cultivating a positive attitude towards energy conservation and strong social norms of peak-hour energy reduction is important.
- Different factors need to be considered/targeted when estimating/promoting varies DR behaviors in different income groups
- The assumption of low-income households being more concerned about cutting costs and less concerned about the environment is not valid.
- Providing financial incentives may not be the only way or the most effective way to promote DR.

Home Energy Management System (HEMS)

HEMS: Hardware and/or software systems that can monitor and provide feedback about a home's energy usage.

Visualization of energy consumption

+

Smart control of home electronics

- Show **daily electricity consumption**, check for excess consumption, and help reach the goal of energy saving.
- Allows users to operate HEMS through a **smartphone**.
- Save electricity bill. Through connecting HEMS to home appliances, HEMS can **automatically manage appliances**, and minimize energy cost with certain **renewable** technologies.

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Home Energy Management System (HEMS)

"Smart home services are considered one of the most promising potential markets"

By 2022 there will be nearly 70 million smart homes in the US

.
By 2030 Japan plans to have HEMS installed in every home, after having smart meters installed in households in 2024.

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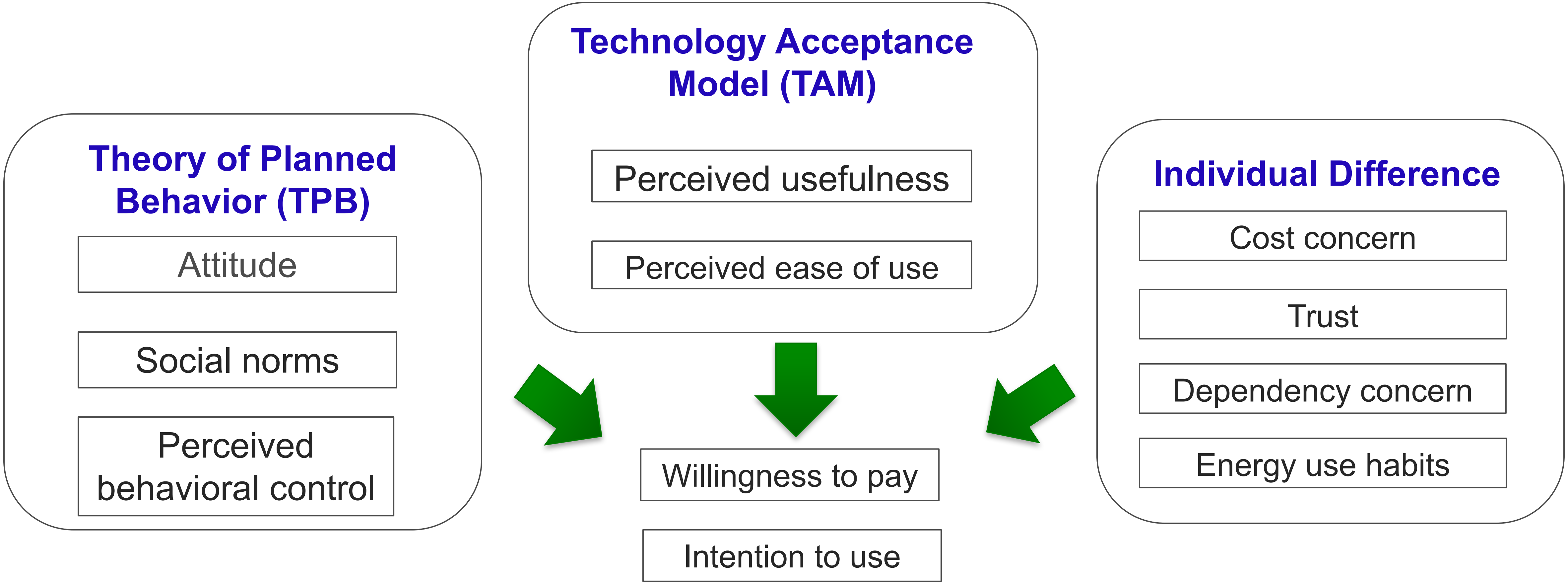
Public Acceptance of HEMS in New York and Tokyo

- **Goal**
  - To investigate U.S. and Japanese residents' willingness to adopt, pay for, and attitude towards HEMS' services, and the barriers residents may face
- **Sample**
  - 1193 from New York
    - Gender: 593 Females, 600 Males
    - Age: 30-69 years old (average: 51.58)
    - Home ownership: Participants were home owners or a family member owned the house
  - 1226 from Tokyo
    - Gender: 641 Females, 585 Males
    - Age: 30-69 years old (average: 52.98)
    - Home ownership: Participants were homeowners or a family member owned the house

Theoretical Framework



Example of Survey Design – HEMS Can …

- Control home appliances automatically and smartly.
  - Automatic control of air conditioners, water heaters, photovoltaic panels, etc.
  - Automatic scheduling of washers and dryers during times of lowest consumption.

- Detect waste of electric consumption and optimize operations of appliances in such a way as not to sacrifice your comfort and convenience.

- Through HEMS and smartphone interfacing, you can turn the power on or off to your air-conditioners and schedule appliance operation remotely.

Example of Survey Design – HEMS Helps…

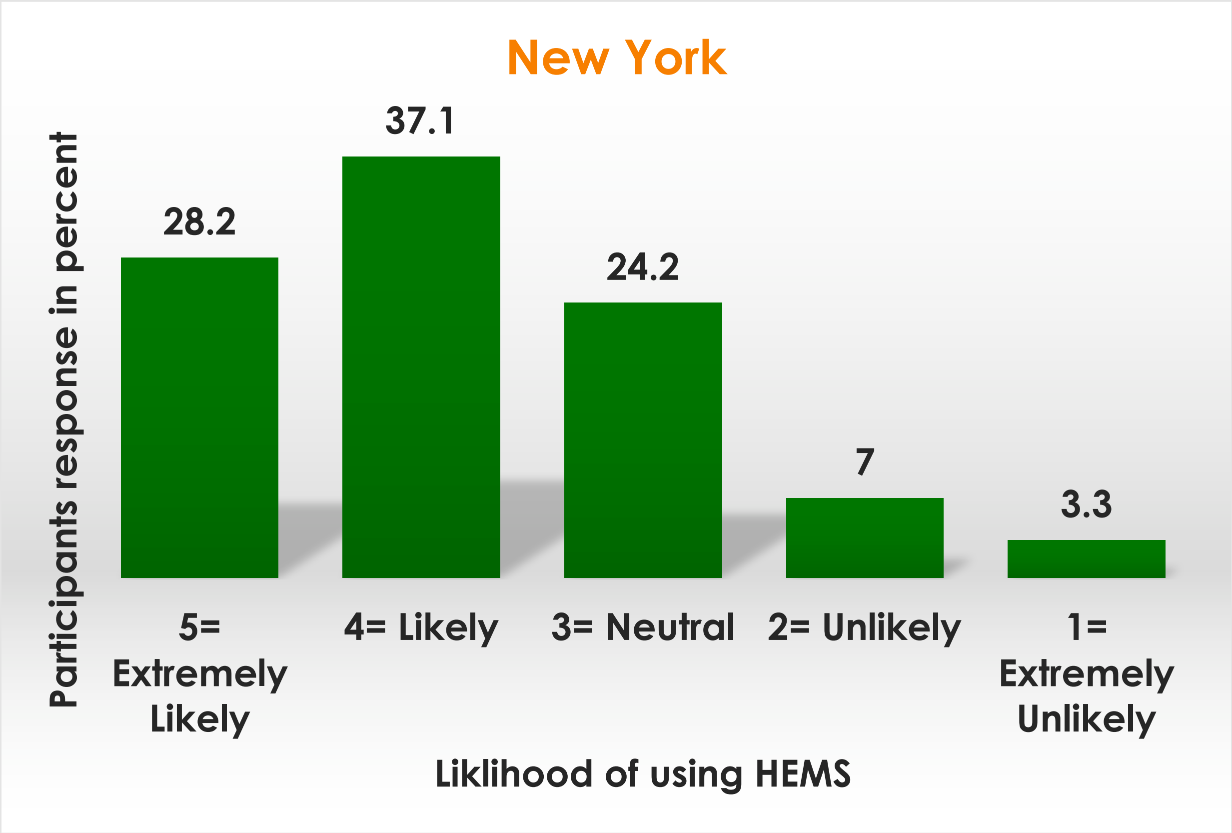
- HEMS helps to ensure a stable and efficient energy market.

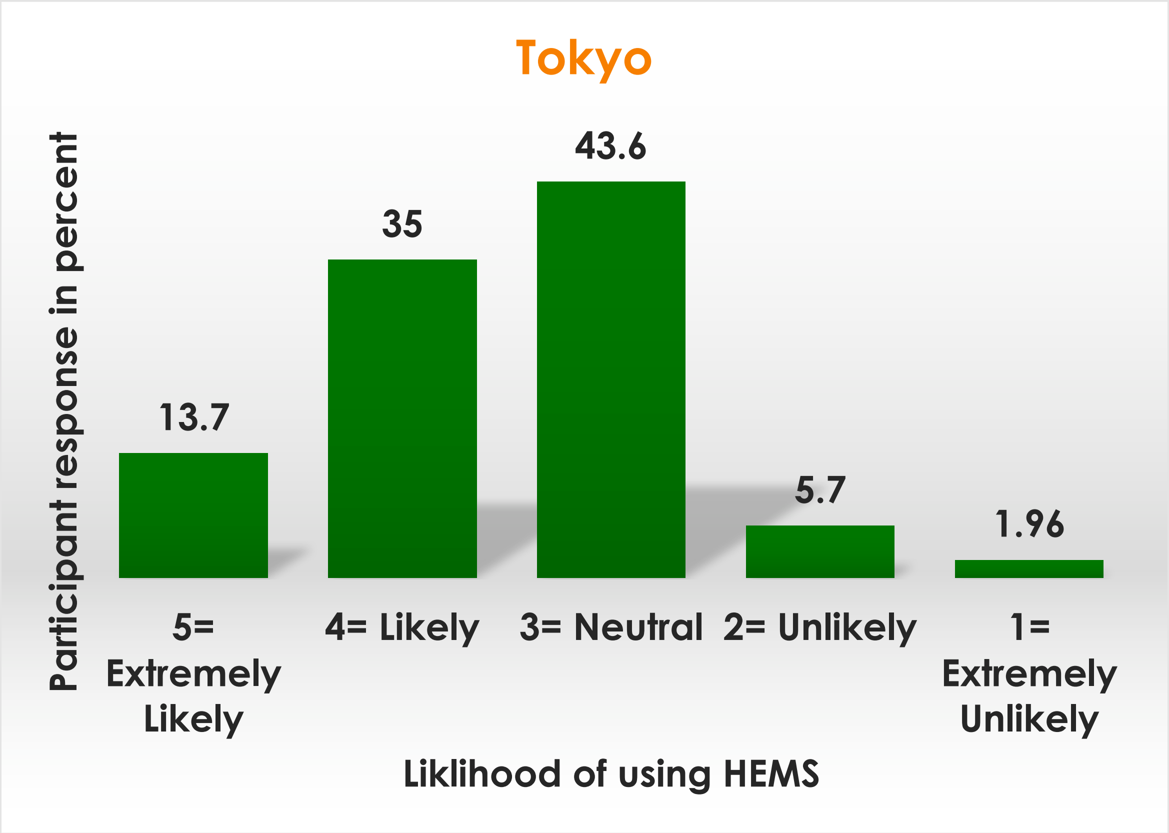
HEMS works off of a notion of demand response (DR), a measure of reduction of peak energy consumption. For example,

- In the midsummer afternoon and midwinter evening, the peak time periods for electric power demand, electricity prices may be raised.
- HEMS automatically controls appliances in such a way to reduce energy consumption, saving money on your electric bill, for example, by adjusting the thermostat within a 1-2 degree range.
- In the future, various DR programs will be available to suit the needs of the individual.

Intention to Adopt HEMS

"It is likely that I will use HEMS service in the future."





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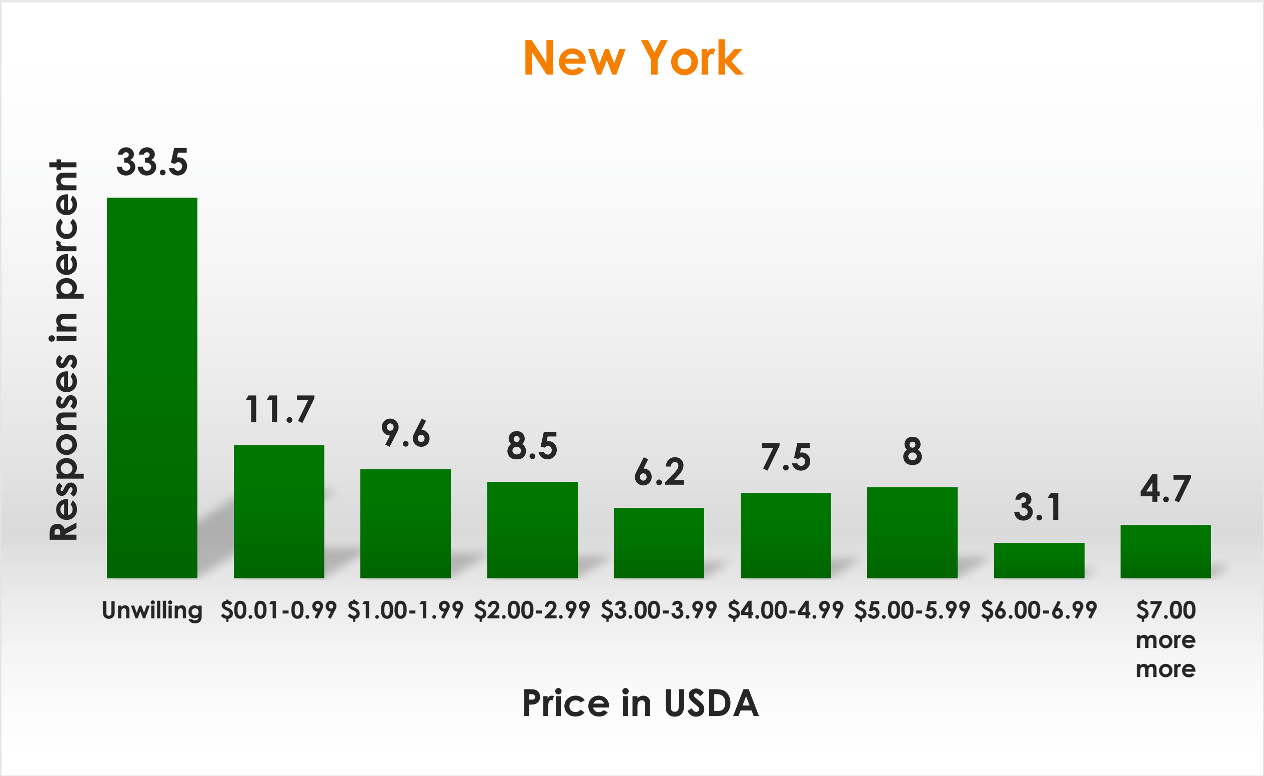
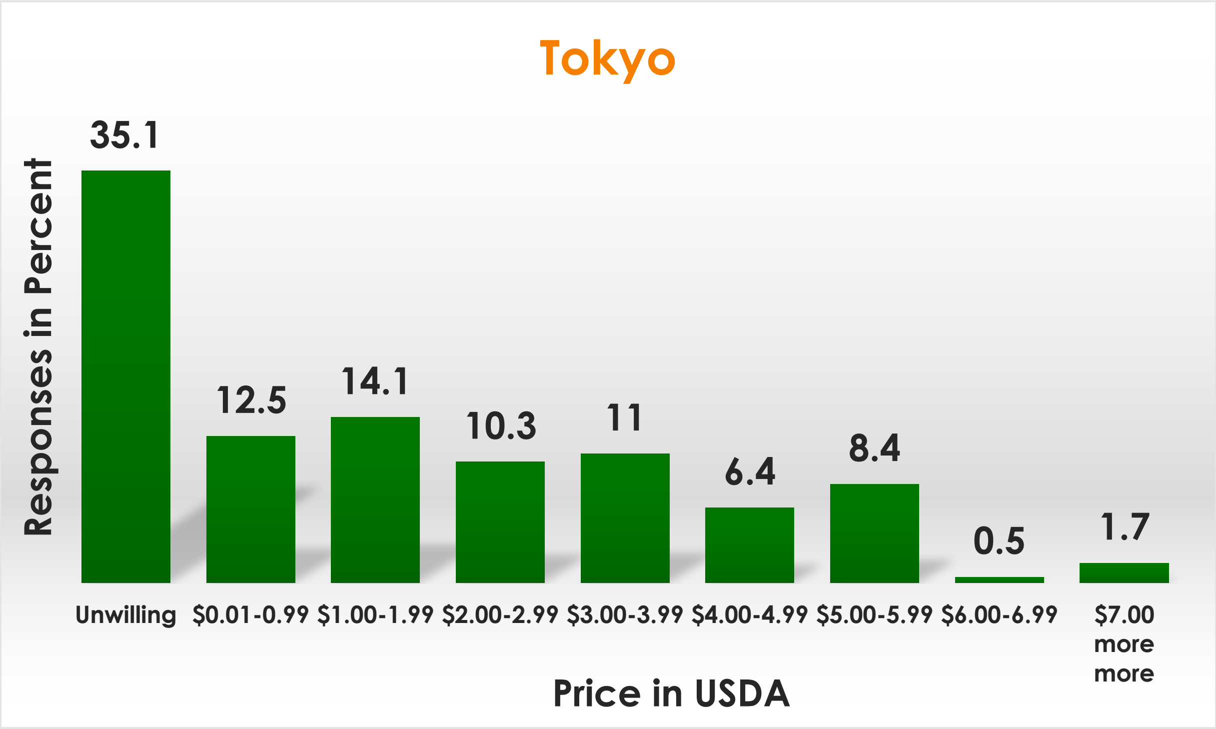
Willingness to Pay (WTP) for HEMS

Question: “How much are you willing to pay if HEMS can automatically control your appliances and minimize energy costs?”





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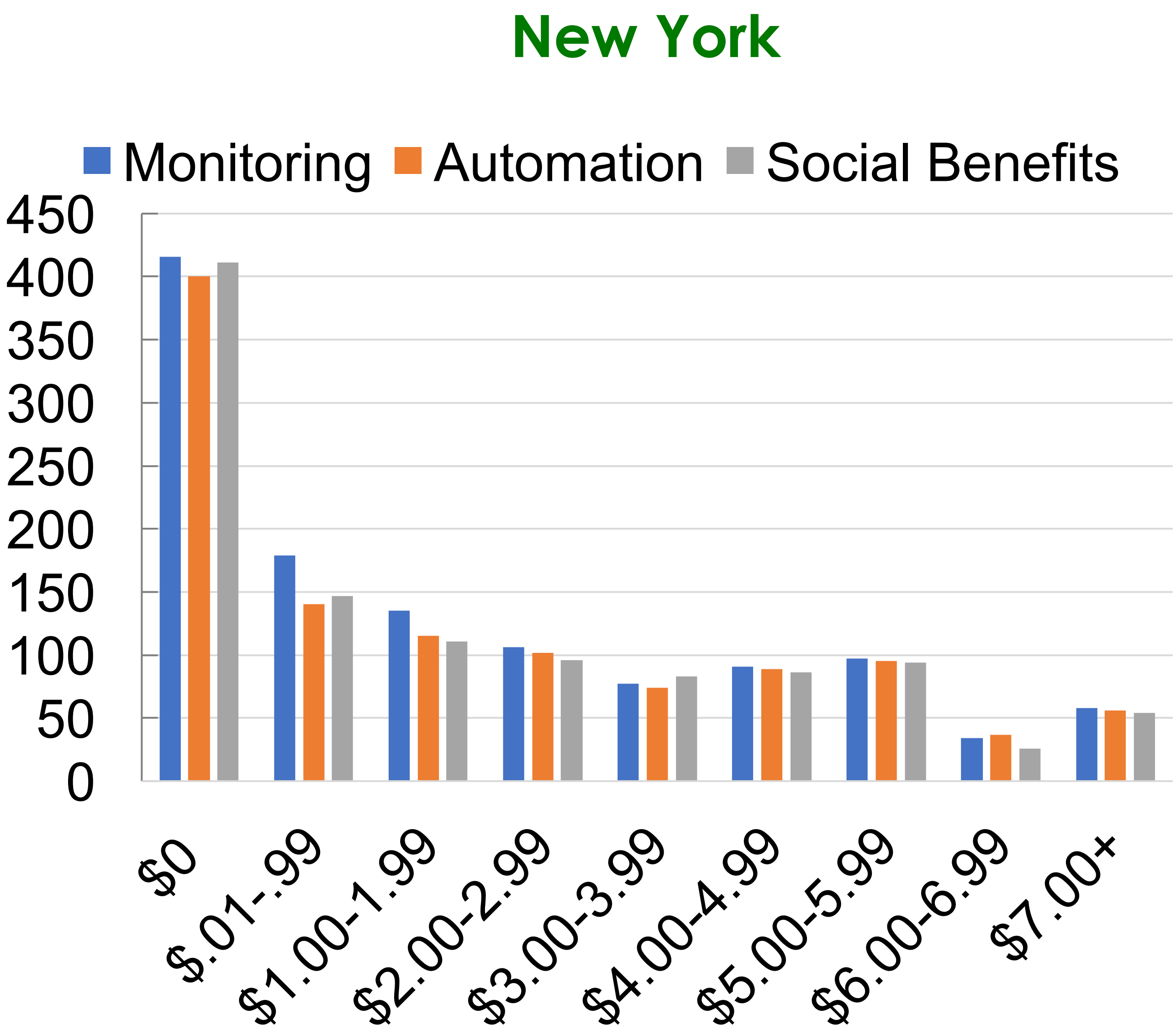
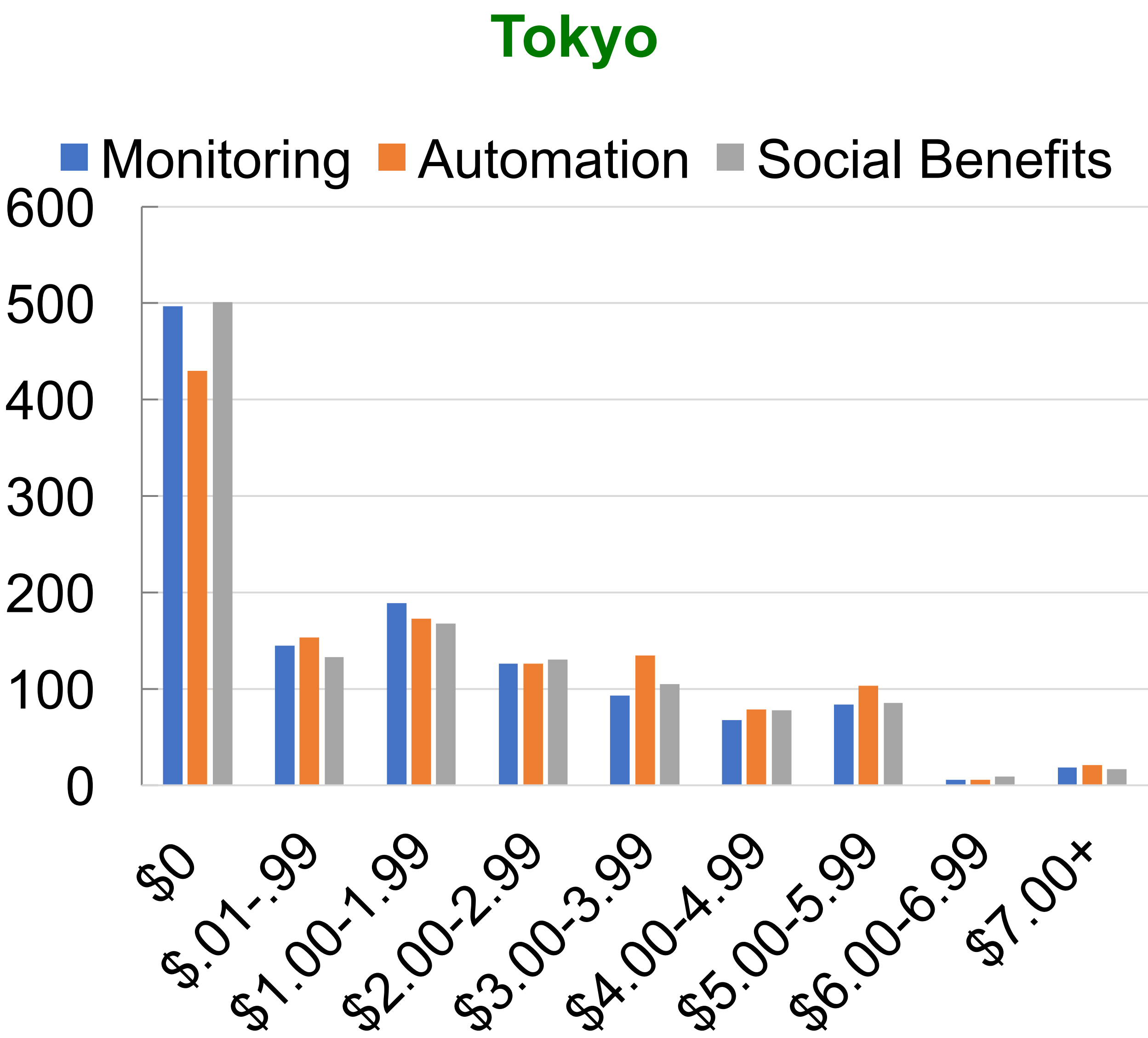
Willingness to Pay for HEMS





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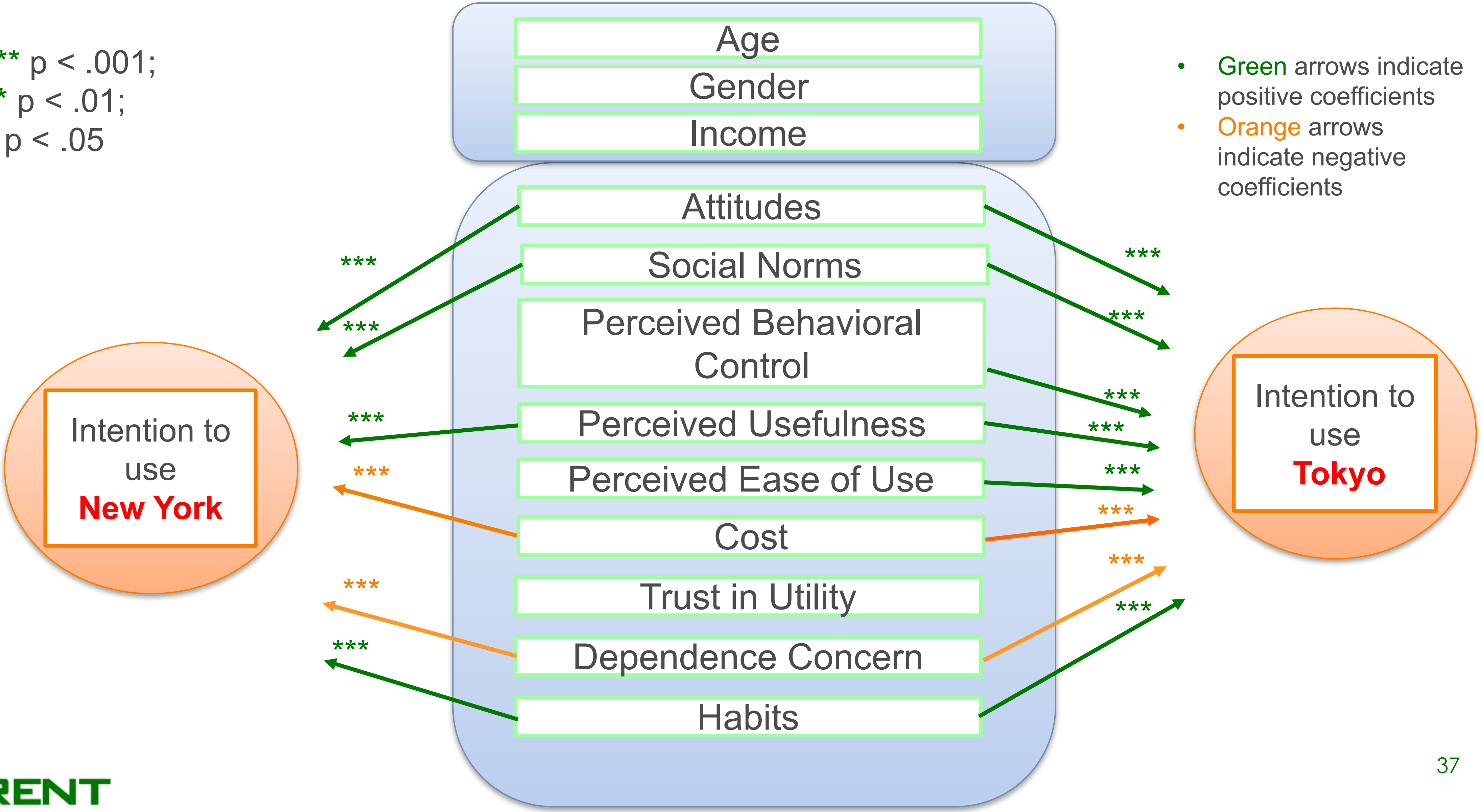
Regression Results on Overall Intention to Use HEMS

*** p < .001;
** p < .01;
* p < .05

- Green arrows indicate positive coefficients
- Orange arrows indicate negative coefficients



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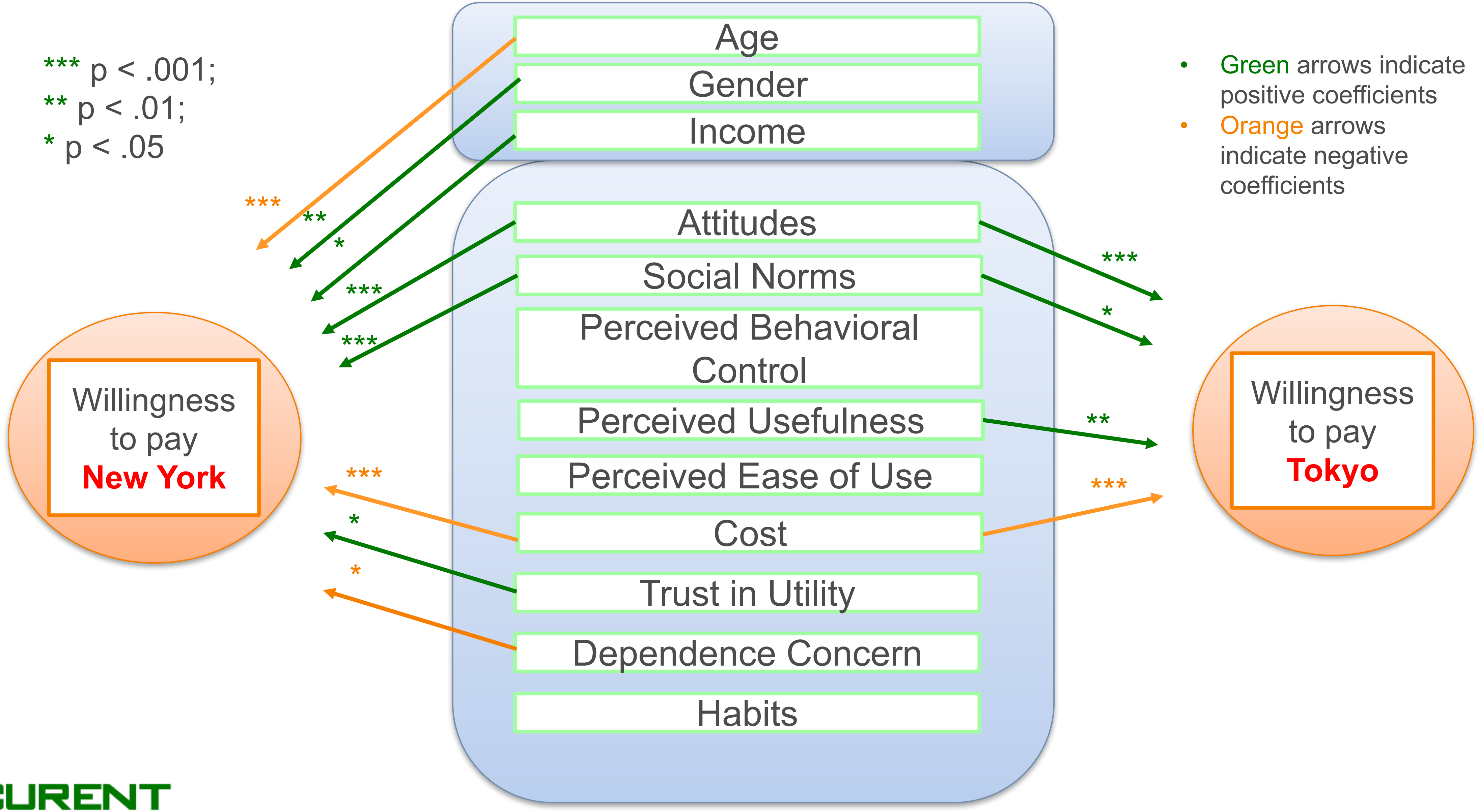
Regression Results on WTP



*** p < .001;
** p < .01;
* p < .05

- Green arrows indicate positive coefficients
- Orange arrows indicate negative coefficients

Conclusions

- Both countries had somewhat positive intention to use HEMS, while U.S. had higher intention to use HEMS.
- Both countries were willing to pay only a little (less than $3) to adopt HEMS.
- N.Y. residents scored higher on most social-psychological variables that were supposed to contribute to higher intention to use and WTP for HEMS.

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Conclusions

- There were some similarities and differences between the factors contributing to intention and WTP, as well as between N.Y. and Tokyo.
  - **Attitude towards HEMS** and **social norms** of using HEMS positively affected both intention to use and WTP in both countries.
  - **Cost concern** negatively affected intention to use and WTP in both countries.
  - **Energy-saving habit** was a positive predictor of intention to use but not of WTP in both countries.
  - **Perceived usefulness** affected WTP in Tokyo, while gender, age, income, trust in utilities and dependency concern affected WTP in New York.

- The results suggest the need to enhance social norms and alleviate cost concerns in promoting HEMS.
- While educational campaigns about the usefulness of HEMS may help in Tokyo, targeting specific customer segments and cultivating trust in utility companies may be more effective in New York.

Selected Publications

- Xu, X., Chen, C.F., Zhu, X., & Hu, Q. (accept). Promoting acceptance of direct load control programs in the United States: Financial incentive versus control option. Energy.
- Xu, X., **Chen, C.F.**, Washizu, A., Ishii, H., & Yashiro, H. (under review). Willingness to pay for home energy management system: A cross-country comparison. *IEEE Power and Energy Society (PES) General Meeting, 2018.*
- **Chen, C.-F**., Xu, X., & Day, J. (2017). Thermal comfort or money saving? Exploring intentions to conserve energy among low-income households in the United States. *Energy Research and Social Science,* 26, 61-71.
- **Chen, C.-F**., Xu, X., & Arpan, L. (2017). Between the technology acceptance model and sustainable energy technology acceptance model: Investigating smart meter acceptance in the United States. *Energy Research and Social Science*, 25, 93-104.
- D'Oca, S., **Chen, C.-F**., Hong, T., & Belafi, Z. (2017). Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings. *Energy Research and Social Science*, 34, 240-251.
- **Chen, C.-F**. Xu, X. & Frey, R. S. (2016). Who wants solar water heaters and alternative fuel vehicles? Assessing social-psychological predictors of adoption intention and policy support in China. *Energy Research and Social Science*, 15, 1-11.

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