Blending Behavioral Science and Physics-Based Models Inform Equitable Decarbonization Pathways in the US Housing Stock

Preprint

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Blending behavioral science and physics-based models inform equitable decarbonization pathways in the US housing stock

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ABSTRACT

A just energy transition is an imperative the Department of Energy, emphasizing the equitable distribution of benefits through energy-efficient and decarbonizing household technologies. Understanding the factors that increase a household's willingness to adopt these technologies helps policymakers implement more targeted and effective approaches. Our research addresses this by blending 550,000 housing stock types and energy simulation data with a nationally representative survey on residential technology adoption and decision-making (n=10,000). We identify energy equity gaps across tenure and income, highlighting disparities in energy burdens and insecurity. Findings show that households with prior modification experience are more willing to renovate, suggesting that small-scale retrofit programs could foster greater willingness. Energy secure but burdened homeowners are least willing to modify, highlighting the need to consider energy bill perceptions in policy design. Nearly half of US households that are energy burdened also face energy insecurity, with a significant gap in assistance for low-income households. We emphasize the need to understand household perceptions to improve policy. This research underscores the importance of understanding household behaviors to improve policy effectiveness, offering actionable insights for policymakers to promote equitable housing upgrades and advance a decarbonized future.

Introduction

"Close the door, you'll let the heat out," is a plea from elders, recalling a time when energy was scarce, much like President Jimmy Carter's call in the 1970s for Americans to lower their thermostats and wear sweaters during an energy crisis (Carter 1977). These actions – wearing sweaters and lowering thermostats– reflect behaviors adopted when energy needs can't be met, highlighting a crucial aspect of energy equity.

A just energy transition is an imperative of the Department of Energy. Energy justice, which aims to make energy accessible, affordable, clean, and democratically managed, is crucial for achieving this goal. Indicators like energy burden and energy insecurity help identify households facing financial difficulties in meeting their energy needs. Lower-income and disadvantaged populations face significant barriers in adopting home energy upgrades due to high upfront costs and geographic factors. Homeownership also influences technology adoption, with homeowners more likely to invest in energy-efficient upgrades compared to renters, who face split incentives between themselves and landlords. Despite these challenges, understanding the motivations, perceptions, and prior experiences of households can inform more effective policies.

Research indicates that stated values and intentions do not always translate into action, especially in the context of energy consumption and home renovations (Conner and Norman 2022; Tawde, Kamath, and ShabbirHusain 2023). However, past behavior, particularly in making home modifications, can be a strong predictor of future actions. This study aims to understand how sociodemographic factors, energy insecurity, energy burden, and prior modification behaviors influence intentions to renovate dwellings.

By integrating data from the ResStock™ and UPGRADE-E™ datasets, this research identifies energy equity gaps across tenure and income levels, highlighting disparities in energy burdens and insecurity. Findings suggest that prior modification experience increases willingness to renovate, indicating the potential for small-scale retrofit programs to foster greater adoption of energy-efficient technologies. Additionally, the study emphasizes the importance of understanding household perceptions and financial constraints to design effective and equitable policies. This research contributes to a more just and inclusive energy transition, providing actionable insights for policymakers to promote equitable housing upgrades and advance a cleaner energy economy.

Background

Serving low- and moderate-income households in the energy transition

Historically, US policy makers have favored market-based instruments to deliver on policy goals, such as rebates or tax credits to increase uptake of specific technologies (Berman 2022). While these instruments efficiently distribute benefits, they can create inequities in terms of who can access these benefits, where higher-income households have an easier time accessing benefits than lower-income households. Recognizing this limitation, many policymakers have enacted initiatives and laws that center and serve low- and moderate-incomes households. The Biden-Harris Administration established a Justice40 Initiative in which 40% of the overall benefits of certain federal investments should flow to disadvantaged communities (Office of Energy Justice and Equity 2022). The Inflation Reduction Act of 2022 specifies minimum requirements for benefits to be distributed to disadvantaged communities and increases Home Energy Rebates (sections 50121 and 50122) for low- and moderate-income households (Rep. Yarmuth 2022). Area Median Income (AMI), a measure of relative wealth of household in relation to a households' surrounding cost of living and size, supports households in qualifying as low-income (0% AMI-80% AMI) or moderate income (80% AMI-150% AMI) for Home Energy Rebates (HUD 2023).

Centering "the concerns of marginalized communities and aims to make energy more accessible, affordable, clean, and democratically managed for all communities" (Cooper 2019) can make the energy transition more just and fair. Energy justice is a critical lens to understand and situate energy resources, distributional issues, and pluralistic needs (Barragán-Contreras 2023). Taking a more pluralistic approach can support more just policies and procedures by grappling with the many different ways that people need, perceive, use, and are affected by, energy systems (Schmidt and Stenger 2023). Out of a need for simple and pragmatic metrics, indicators have been developed to approximate aspects of energy justice (Sovacool and Dworkin 2015). Energy burden, a measure of energy expenditures relative to the overall household income, has been persistently high among low-income households, particularly in the American

South, rural America, and minority communities (Brown et al. 2020), where high energy burden means that a household spends 6% or more of their income on energy bills. Energy burden is useful for identifying households that are facing financial burdens, but also misses how households need energy. Energy insecurity, an indicator of a household's inability to afford their basic energy needs, offers a dimension to understand how households forgo their energy needs to meet other needs such as food, shelter, and transportation (Graff et al. 2022). A household's difficulty paying energy bills can indicate energy insecurity, where difficulty may mean missed payments, utility disconnection, or modifying behavior to decrease energy bills (e.g., not cooling during hot outdoor temperatures) (Memmott et al. 2021). Difficulty with paying energy bills can also help to contextualize a household's perception of their situation and energy needs, whereas energy burden reports decontextualized financial burdens. Of course, there are other measures, dimensions, and critical frames of energy justice worth exploring, particularly for non-access (i.e., energy poverty) and procedural democracy (i.e., energy democracy), but these aspects of energy justice fall beyond the scope of this work. Regardless, understanding and correcting energy injustice is critical to achieving a clean energy future that serves all communities.

Understanding socioeconomic factors influencing home energy upgrades

Lower-income and disadvantaged populations face considerable financial barriers in making these home upgrades (Sovacool, Martiskainen, and Furszyfer Del Rio 2021). Whole-home electrification can cost $40,000-50,000 (Walker, Less, and Casquero-Modrego 2023). Additionally, research suggests that geographic factors are highly related to energy-efficient technology adoption (L. W. Davis 2023). Researchers from the Netherlands recently proposed that geographical factors are highly influential in residential uptake of energy-efficiency or decarbonization measures (Halleck Vega, van Leeuwen, and van Twillert 2022). Addressing this topic in the United States, work from some of the authors of this paper looked at the role of regionality in technology adoption using the UPGRADE-E dataset (Antonopoulos et al. 2024), finding significant regional variation and higher general decarbonization technology uptake in the Western region of the United States.

Financial factors also influence perceptions toward adoption. The main motivations for adopting smart home technologies include not only financial savings and benefits, but also the ability to help the environment and increase quality of life (Li et al. 2021; Gravert et al. 2024). However, being environmentally conscious and actively concerned about energy efficiency may not be enough to lead to the adoption of energy-efficient technologies and specific incentives may be needed to encourage the adoption of such measures (Pelenur 2018) Of course, intention does not always lead to action. High upfront costs and insufficient information available about the technologies prove to be barriers, especially for low-income households (Gravert et al. 2024; Li et al. 2021).

Aside from the above-mentioned factors, dwelling characteristics seem to be a contributor of home technology adoption. Among several other motivators, ownership of a residence is an important driver of technology adoption. In addition to that, homeowners are more likely to invest in home energy upgrades than renters, such as adding or replacing insulation and installing energy-efficient windows when they first move into their home, rather than later (Ameli and Brandt 2015). Other studies have shown that renter-occupied dwellings are less likely to have energy-efficient technologies and are less likely to be insulated in the attic or ceiling compared to owner-occupied dwellings (L. Davis 2010; Gillingham, Harding, and Rapson 2012). However, although renters are less likely to invest in permanent energy-efficient features in their homes, they may still invest in technologies with a shorter life cycle, such as energy-efficient appliances and light bulbs (Ameli and Brandt 2015).

Gaps between intentions and actions when renovating for decarbonized technologies

A person's stated values, attitudes, or intentions don't always match their actions (Rogers 2003; Godin, Conner, and Sheeran 2005). For instance, many people report they are concerned about climate change and understand the need to save energy, but don't take steps to reduce their energy consumption (Abrahamse and Steg 2011). People can also respond with what they believe is socially desirable, which contributes to a growing gap between what people say they would do versus how they act, which is a highly prevalent phenomenon in environmental and pro-social contexts like energy consumption (Kilian and Mann 2021). However, when values, attitudes or intentions are strong or situated in morality, they tend to be a more reliable predictor of behavior (Godin, Conner, and Sheeran 2005; Conner and Norman 2022).

Past behavior can also be a reliable predictor of future behavior (Aarts, Verplanken, and van Knippenberg 1998), particularly when decisions are repeated. Interventions and programs have supported habitual behavioral change in the residential energy sector, like decreasing energy usage through habits and timely feedback (Lee et al. 2020); but understanding how to decrease the gap between reported intentions and actions in more discrete, low-frequency decision-making, like renovating one's dwelling, needs more attention.

To fully understand intentions to modify one's dwelling, it is necessary to consider motivations and preferences. One of the key factors is the lack of awareness and familiarity with energy-efficient technologies, which can make homeowners less willing to adopt them (Mills and Schleich 2012; Raimi and Carrico 2016). The strategies and methods employed to disseminate information play a significant role in influencing public perceptions and responses to diverse energy technologies (Boudet 2019). However, people with more knowledge about some decarbonization technologies are also less likely to adopt such technologies. Higher levels of energy knowledge can lead to a better understanding of the uncertainties of some technologies; therefore, it is preferrable to wait to adopt until a more concrete policy supporting this innovation is developed (Cha et al. 2024). Another factor that helps build perceptions towards home decarbonization is place-based attachments and identities. In this context, when an energy technology disrupts place-attachments, for example, homeowners may perceive it negatively and are less likely to adopt them (Devine-Wright 2011; Boudet 2019).

In this research, we aim to understand opportunities for serving low- and moderate-income households. Specifically, we aim to analyze how intentions to modify one's dwelling might be impacted by sociodemographic characteristics, energy insecurity, energy burden, and one's prior modification behaviors. We use ResStock™ and UPGRADE-E™ to understand these interactions. Ultimately, this research seeks to contribute to the development of a more just and inclusive energy transition that ensures all households can benefit from a cleaner energy economy.

Methodology

We blended and analyzed publicly available datasets to answer questions about residential adoption for energy efficient building technologies, UPGRADE-E, as well as residential energy and housing stock, ResStock 2022.1 Release.

Data sources

The Understanding Patterns Guiding Residential Adoption and Decisions about Energy Efficiency (UPGRADE-E) database represents a survey of 10,000 U.S. households. We used a national-scale survey to understand residential energy technology uptake and decision-making. To develop the survey, we first interviewed 121 individuals who identified as decision-makers within their households regarding planned or completed projects (Biswas et al. 2024). We used the insights of these interviews to develop a survey that was distributed to 10,000 households across the United States. The overarching topics approached in the survey include information about the respondent, their household, their residence, building modifications they have made (including building technology upgrades), and their preferences, motivations, barriers, and sources of information. Methodologies surrounding the survey, as well as a regional analysis of results can be found in detail in a previous publication by the authors (Antonopoulos et al. 2024).

ResStock 2022.1 Release was used to estimate the housing stock and impacts from energy efficiency upgrades (Liu, Brossman, and Lou 2023). The highly granular dataset represents 550,000 unique dwelling types spanning geographies, incomes, building types, tenure, vintage, heating fuels, insulation levels, appliance types, and many other household features, with modeled outputs describing energy, emission, upgrade costs, and utility bill impacts. Upgrade costs are estimated for national averages and utility bill impacts are combination of flat level and volumetric, state-average rates.

Together, the datasets represent a rich repository of home energy technology and modification decision-making results, the largest of its kind to-date, as well as the most granular U.S. housing stock model. The abundance of contextual considerations within these datasets provides a robust resource for continual analysis, with possibilities for considering crosscuts of data from a variety of perspectives. The analysis in this paper combines the UPGRADE-E dataset with NREL's ResStock to understand interactions between energy burden, energy insecurity, and willingness to modify (i.e., intentions).

Multifamily buildings, particularly those with more than 5 units, have a greater concentration of shared HVAC and water heating than single family dwellings, requiring whole-building upgrades (Reyna et al. 2022; EIA 2018). Decision-making at the household level for dwellings with 4 units or fewer allows for individual autonomy that does not rely on coordination across dwellings - as is common for large multi-family buildings. Retrofitting manufactured housing also presents a challenge in terms of feasibility. Ongoing field demonstrations have proven successes but need more broad application (Lubliner, Ueno, and Burkett 2019). For these reasons, this work focuses decision-making for residents of single-family homes and small multifamily homes with four units or fewer.

Data Harmonization

Data harmonization assists in the blending of demographic data across time and place (Noble et al. 2011) and facilitates with the ability analyze large, representative studies together, which increase comparability and statistical power (Ruggles 2013). By centering shared household demographics in the UPGRADE-E and ResStock data, we harmonized dataset on the following simplified characteristics:

- State (AL, AK, etc.),
- Building geometry: single-family or multifamily,
- Dwelling vintage: pre-1980 or post-1980, and
- Heating fuel: electricity, natural gas, propane, fuel oil, other, none.

All data from UPGRADE-E was included as is (i.e., not averaged) to hold the integrity of each respondents' answers. We aggregated the ResStock dataset based on the characteristics above and the upgrades modeled in to support data harmonization in each segment type (Mayernik and Stenger 2023). Area Median Income and the household's county were also included in the ResStock using Housing and Urban Development's occupancy and income brackets for each city or county region, based on the detailed methodology of Liu et al. (2023). We averaged the following ResStock outputs for each upgrade modeled by:

- Baseline energy consumption and energy savings for upgrade (MBtu)
- Baseline utility and gas bill and utility and gas bill savings for upgrade ($-2019)
- Baseline energy burden and energy burden after upgrade (%)

For each housing segment, we also counted the total number of modeled dwelling units and estimated the number of households represented. The scope of the research focuses on single-family homes and small multifamily homes with four units or fewer. We randomly imputed values for UPGRADE-E dataset where respondents reported they did not know an answer to a categorical question (e.g., "what is the age of your home?"). For each "not available" value, we iterated five times to randomly sample variables and reduce the risk of outliers. The imputation (i.e., bootstrapping) methodology allows for greater use of the dataset and simplicity in methodology to increase replicability for future studies. We mitigated tradeoffs for bias and variability given the representativeness of the data and large sample size. A clear limitation of this approach for the dataset are that some of the categories are not independent; for instance, higher income households tend to have larger dwelling sizes. Last, we analyzed and confirmed the reported (i.e., UPGRADE-E survey responses) and modeled values (i.e., ResStock) for energy bills and household income aligned after data harmonization.

Data Analysis

Data that is fully complete for each variable is considered. If a survey respondent did not respond to a question central to the analysis, the respondent's answers were excluded. We examined the effect of a respondent's willing to modify relative to their reported action of having modified their dwelling. In doing so, we aim to examine gaps between intentions (e.g., willingness to modify) relative to action (e.g., actual home modification) (Kahneman 2011). We assessed respondents' willingness to modify in UPGRADE-E across 7 technologies by converting responses to a value (i.e., Likert-scale), where respondents who selected "No" scored a 0; “Need more information” scored a 1; “Maybe” scored a 2; “Yes, provided my rent doesn’t increase by much” scored a 3; and “Yes” scored a 4.

Results

We explored respondents' willingness to have their dwellings renovated and how this interacted with prior experiences with modification, tenure, income, energy insecurity, and energy burden. A gap in energy use relative to energy demands can be indicated when households cannot pay their energy bills or modify their behavior to decrease energy use. We show the distribution of UPGRADE-E respondents with their reported energy expenses (i.e., utility bills) relative to the proportion of households that reported having difficulty paying their utility bills, an indicator of energy insecurity, as shown in Figure 2 (Cooper 2019).

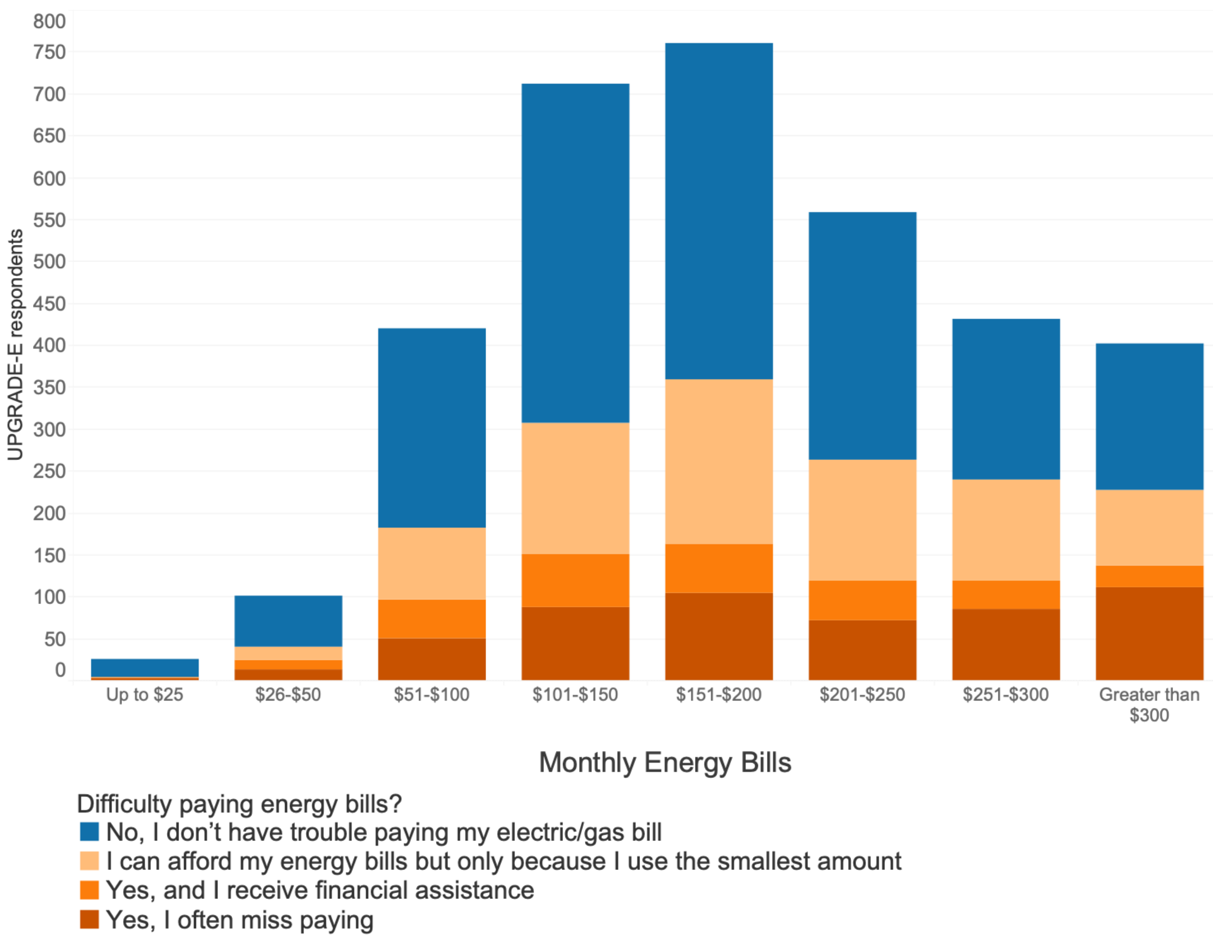

Figure 2. Distribution of energy expenses for UPGRADE-E respondents.

While 52% of respondents reported having no difficulty paying their utility bills, 23.5% shared that they could afford their utility bills only because they use the smallest amount of energy possible (e.g., they reduce their energy usage relative to their needs), and 15.7% reported that they often miss paying a utility bill. In these analyses, data was excluded if it was not available or categorized as 'other.' Energy burden provides a view into energy equity gaps as well, where households are considered energy burdened when they spend 6% or more of their income on energy needs (Colton 2012). We show the distribution among respondents who are likely energy burdened based on the integration with ResStock results and map this distribution to AMI and reported difficulty in paying energy bills in Figure 3.

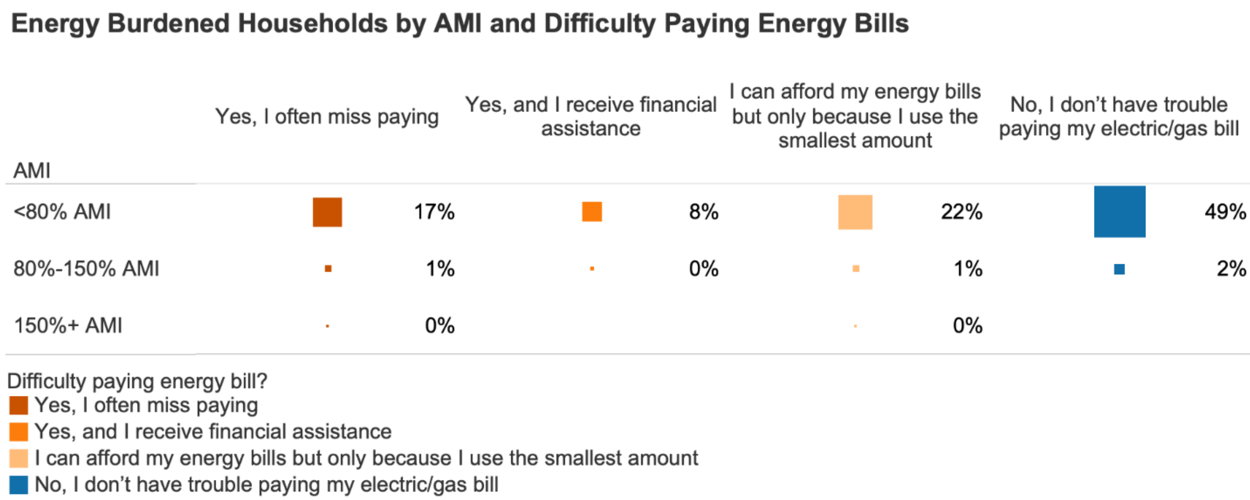

Figure 3. Energy burdened households by Area Median Income (AMI) and their difficulty to pay energy bills.

Seventeen percent of energy burdened households are low-income and often miss energy bill payments—a clear indicator of energy insecurity. Like prior work on energy burden, 95% of energy burdened households (>6%) are low-income (0%-80% AMI) (Brown et al. 2020). The analysis also shows that 51% of energy burdened households do not have difficulty paying their energy bills (i.e., these households report being energy secure). By using both measures, researchers and policymakers can target benefits toward households that are struggling with their energy bills and have a high energy burden.

We also examined how a household's willingness to modify (i.e., renovate) their dwelling might interact with tenure, energy security, energy burden, and prior experience of modifying their dwelling in Figure 4. Energy secure households reported they had no difficulty paying their energy bills, while energy insecure households reported they had difficulty.

Figure 4. Willingness to modify by tenure, energy insecurity, energy burden, and prior experience modifying their dwelling.

Households that had previously made a modification to their dwelling reported a higher willingness to modify their dwelling in the future compared to households that did not, suggesting that prior behavior may inform future behavior – or at least an openness to renovations. Renters were more willing to have their dwelling modified than owners, possibly because the survey question allowed for renters to respond with '*Yes, provided my rent doesn't increase by much*.'

There was little difference in willingness to modify between households with and without energy burdens, and between energy insecure and secure households. The one exception to this pattern was energy secure households that were also energy burdened. Energy secure and energy burdened owners were the least willing to modify their dwelling, which indicates that the perception of energy bills is an important factor in targeting homeowners willing to renovate their dwellings.

Discussion and Conclusion

Blending behavioral and housing stock datasets yielded an enriched analysis of energy equity gaps across tenure and income and provides evidence for a more people-centered approach for energy policy and programs.

Past behavior may inform future behavior. Households with prior experience making modifications to their dwellings report a higher willingness to modify their dwelling in the future. The measure of prior modification shows the importance of experience with renovations when considering future energy efficiency and decarbonizing projects. Exploring how households could get experience with modifying their dwelling, even in small ways, may help households to be more willing to modify in the future. This finding may also suggest a benefit for programs that serve many households with small modifications (i.e., wide retrofits). While programs that serve fewer households with major modifications (i.e., deep retrofits) have many benefits, including lower administrative costs and more robust energy investments, serving many households may increase the willingness for more households to retrofit or renovate their dwellings in the future.

Energy secure homeowners who are also energy burdened show the least willingness to modify their dwellings, underscoring the crucial role of energy bill perceptions. The lack of a strong correlation between energy burden and willingness to modify suggests that using this metric alone for targeted policy intervention may be insufficient for effective implementation. While energy burden is a valuable measure of energy justice and financial stress, understanding households' perceptions of the difficulty in paying their bills (i.e., approximating energy insecurity) could enable policymakers to more accurately identify and engage willing participants in residential energy efficiency and decarbonization programs.

Renters showed a slightly higher willingness to modify their dwelling, if it doesn't increase rents. Serving renters has been a challenge for program implementation because landlords often pay for upgrades while renters benefit from potential bill savings (i.e., a split incentive). Exploring the creative deployment of financing structures, such as tariff on-bill financing, could increase participation among renters and their landlords (US EPA 2023).

The study highlights the intersection of energy burden and energy insecurity, providing a more holistic understanding of energy equity. By combining energy burden, a common measure of affordability, with a systematic examination of energy insecurity (i.e., difficulty paying utility bills), we uncovered significant insights. Notably, 48% of energy burdened households reported having difficulty paying their utility bills or altering their behavior to meet these costs. In addition, 95% of energy burdened households, defined as those spending 6% or more of their income on energy bills, are classified as low-income (0% - 80% AMI). Within this demographic, only 9% receive bill assistance, and 15% often miss payments, illustrating a substantial gap between the availability of assistance programs and the needs of households. This discrepancy underscores the need for more effective policies and support systems to address the widespread issue of energy insecurity and ensure that assistance reaches those most in need.

The harmonized datasets help to assess households' perceived difficulty in paying energy bills and their financial hardships. Bootstrapping the UPGRADE-E dataset supported greater implementation and allowed for higher granularity in analysis, but also presents risks of bias – particularly toward the mean. Manufactured and large-scale multifamily housing were excluded from the UPGRADE-E dataset, suggesting a need to better represent this housing segment, and it presents a bias towards single-family and small multifamily housing.

Future work is also needed to move from descriptive to predictive analysis, identifying sensitivities to incentives for energy insecure and burdened demographics when transitioning to energy efficient and decarbonized technologies. More research is needed to better understand how to close the gap between intentions and actions for residential technology adoption, particularly among households facing energy inequities. Future work could also explore the technical potential of deploying various energy-bill reducing technologies to energy insecure households that are highly willing to modify their dwelling.

References

Aarts, Henk, Bas Verplanken, and Ad van Knippenberg. 1998. "Predicting Behavior From Actions in the Past: Repeated Decision Making or a Matter of Habit?" *Journal of Applied Social Psychology* 28 (15): 1355–74. https://doi.org/10.1111/j.1559-1816.1998.tb01681.x.

Abrahamse, Wokje, and Linda Steg. 2011. "Factors Related to Household Energy Use and Intention to Reduce It: The Role of Psychological and Socio-Demographic Variables." *Human Ecology Review* 18 (1): 30–40.

Ameli, Nadia, and Nicola Brandt. 2015. "Determinants of Households' Investment in Energy Efficiency and Renewables: Evidence from the OECD Survey on Household Environmental Behaviour and Attitudes." *Environmental Research Letters* 10 (4): 044015. https://doi.org/10.1088/1748-9326/10/4/044015.

Antonopoulos, Chrissi A., Tracy L. Fuentes, Kieren H. McCord, Adrienne L. S. Rackley, and Saurabh Biswas. 2024. "Regional Assessment of Household Energy Decision-Making and Technology Adoption in the United States." *Energy Policy* 185 (February):113940. https://doi.org/10.1016/j.enpol.2023.113940.

Barragán-Contreras, Sandra Jazmin. 2023. "Towards More Pluralistic Energy Justice Frameworks." In *Handbook on Energy Justice*, 240–52. Edward Elgar Publishing. https://www.elgaronline.com/edcollchap/book/9781839102967/book-part-9781839102967-24.xml.

Berman, Elizabeth Popp. 2022. "Thinking like an Economist: How Efficiency Replaced Equality in U.S. Public Policy." In *Thinking like an Economist*. Princeton University Press. https://doi.org/10.1515/9780691226606.

Biswas, Saurabh, Tracy L. Fuentes, Kieren H. McCord, Adrienne L. S. Rackley, and Chrissi A. Antonopoulos. 2024. "Decisions and Decision-Makers: Mapping the Sociotechnical Cognition behind Home Energy Upgrades in the United States." *Energy Research & Social Science* 109 (March):103411. https://doi.org/10.1016/j.erss.2024.103411.

Boudet, Hilary S. 2019. "Public Perceptions of and Responses to New Energy Technologies." *Nature Energy* 4 (6): 446–55. https://doi.org/10.1038/s41560-019-0399-x.

Brown, Marilyn A., Anmol Soni, Melissa V. Lapsa, Katie Southworth, and Matt Cox. 2020. “High Energy Burden and Low-Income Energy Affordability: Conclusions from a Literature Review.” *Progress in Energy* 2 (4): 042003. https://doi.org/10.1088/2516-1083/abb954.

Carter, Jimmy, dir. 1977. “President Carter’s Fireside Chat on Energy.” Washington, D.C.: C-SPAN. https://www.c-span.org/video/?153913-1/president-carters-fireside-chat-energy.

Cha, Min-kyeong, Cory L. Struthers, Marilyn A. Brown, Snehal Kale, and Oliver Chapman. 2024. “Toward Residential Decarbonization: Analyzing Social-Psychological Drivers of Household Co-Adoption of Rooftop Solar, Electric Vehicles, and Efficient HVAC Systems in Georgia, U.S.” *Renewable Energy* 226 (May):120382. https://doi.org/10.1016/j.renene.2024.120382.

Conner, Mark, and Paul Norman. 2022. “Understanding the Intention-Behavior Gap: The Role of Intention Strength.” *Frontiers in Psychology* 13 (August). https://doi.org/10.3389/fpsyg.2022.923464.

Cooper. 2019. “Section 1 - Defining Energy Justice: Connections to Environmental Justice, Climate Justice, and the Just Transition.” *Initiative for Energy Justice* (blog). December 23, 2019. https://iejusa.org/section-1-defining-energy-justice/.

Davis, Lucas. 2010. “Evaluating the Slow Adoption of Energy Efficient Investments: Are Renters Less Likely to Have Energy Efficient Appliances?” w16114. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w16114.

Davis, Lucas W. 2023. “The Economic Determinants of Heat Pump Adoption.” Working Paper. Working Paper Series. National Bureau of Economic Research. https://doi.org/10.3386/w31344.

Devine-Wright, Patrick. 2011. “Place Attachment and Public Acceptance of Renewable Energy: A Tidal Energy Case Study.” *Journal of Environmental Psychology* 31 (4): 336–43. https://doi.org/10.1016/j.jenvp.2011.07.001.

EIA. 2018. “Table B19. Energy Sources, Number of Buildings, 2018.” . . *Energy Sources*.

Gillingham, Kenneth, Matthew Harding, and David Rapson. 2012. “Split Incentives in Residential Energy Consumption.” *The Energy Journal* 33 (2): 37–62. https://doi.org/10.5547/01956574.33.2.3.

Godin, Gaston, Mark Conner, and Paschal Sheeran. 2005. “Bridging the Intention–Behaviour Gap: The Role of Moral Norm.” *British Journal of Social Psychology* 44 (4): 497–512. https://doi.org/10.1348/014466604X17452.

Graff, Michelle, David M. Konisky, Sanya Carley, and Trevor Memmott. 2022. "Climate Change and Energy Insecurity: A Growing Need for Policy Intervention." *Environmental Justice* 15 (2): 76–82. https://doi.org/10.1089/env.2021.0032.

Gravert, Kara, Cristina Poleacovschi, Linnel Ballesteros, Kristen Cetin, Ulrike Passe, Anne Kimber, Diba Malekpour Koupaei, and Forrest Douglass. 2024. "Homeowners' Motivations to Invest in Energy-Efficient and Renewable Energy Technologies in Rural Iowa." *ASCE OPEN: Multidisciplinary Journal of Civil Engineering* 2 (1): 04024002. https://doi.org/10.1061/AOMJAH.AOENG-0010.

Halleck Vega, Solmaria, Eveline van Leeuwen, and Nienke van Twillert. 2022. "Uptake of Residential Energy Efficiency Measures and Renewable Energy: Do Spatial Factors Matter?" *Energy Policy* 160 (January):112659. https://doi.org/10.1016/j.enpol.2021.112659.

HUD. 2023. "Income Limits | HUD USER." 2023. https://www.huduser.gov/portal/datasets/il.html.

Kahneman, Daniel. 2011. *Thinking, Fast and Slow*. New York, NY, USA: Farrar, Straus and Giroux.

Kilian, Sven, and Andreas Mann. 2021. "The Phantom of the 'Responsible Consumer': Unmasking the Intention–Action Gap with an Indirect Questioning Technique." *Sustainability* 13 (23): 13394. https://doi.org/10.3390/su132313394.

Lee, Eungkyoon, Myounggu Kang, Jaemin Song, and Myunghoon Kang. 2020. "From Intention to Action: Habits, Feedback and Optimizing Energy Consumption in South Korea." *Energy Research & Social Science* 64 (June):101430. https://doi.org/10.1016/j.erss.2020.101430.

Li, Wenda, Tan Yigitcanlar, Isil Erol, and Aaron Liu. 2021. "Motivations, Barriers and Risks of Smart Home Adoption: From Systematic Literature Review to Conceptual Framework." *Energy Research & Social Science* 80 (October):102211. https://doi.org/10.1016/j.erss.2021.102211.

Liu, Lixi, Jes Brossman, and Yingli Lou. 2023. "ResStock Communities LEAP Pilot Residential Housing Analysis - Detailed Methodology." NREL/TP--5500-88058, 2274781, MainId:88833. https://doi.org/10.2172/2274781.

Lubliner, Michael, Kohta Ueno, and Helen (Lena) W. Burkett. 2019. "Retrofit of Blown Attic Insulation in Existing HUD-Code Manufactured Homes: Needs Assessment Report." NREL/TP-5500-73279; DOE/GO-102019-5188. National Renewable Energy Laboratory (NREL), Golden, CO (United States). https://doi.org/10.2172/1545588.

Mayernik, Jack, and Katelyn Stenger. 2023. “Overview of the Inflation Reduction Act of 2022 (IRA) Home Energy Rebate Tool.” NREL/TP-6A20-86700. National Renewable Energy Laboratory (NREL), Golden, CO (United States). https://doi.org/10.2172/1994288.

Memmott, Trevor, Sanya Carley, Michelle Graff, and David M. Konisky. 2021. “Sociodemographic Disparities in Energy Insecurity among Low-Income Households before and during the COVID-19 Pandemic.” *Nature Energy* 6 (2): 186–93. https://doi.org/10.1038/s41560-020-00763-9.

Mills, Bradford, and Joachim Schleich. 2012. “Residential Energy-Efficient Technology Adoption, Energy Conservation, Knowledge, and Attitudes: An Analysis of European Countries.” *Energy Policy*, Special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy, 49 (October):616–28. https://doi.org/10.1016/j.enpol.2012.07.008.

Noble, Petra, David VAN Riper, Steven Ruggles, Jonathan Schroeder, and Monty Hindman. 2011. “Harmonizing Disparate Data across Time and Place: The Integrated Spatio-Temporal Aggregate Data Series.” *Historical Methods* 44 (2): 79–85. https://doi.org/10.1080/01615440.2011.563228.

Office of Energy Justice and Equity. 2022. “Justice40 Initiative.” Department of Energy. 2022. https://www.energy.gov/justice/justice40-initiative.

Pelenur, Marcos. 2018. “Household Energy Use: A Study Investigating Viewpoints towards Energy Efficiency Technologies and Behaviour.” *Energy Efficiency* 11 (7): 1825–46. https://doi.org/10.1007/s12053-018-9624-x.

Raimi, Kaitlin T., and Amanda R. Carrico. 2016. “Understanding and Beliefs about Smart Energy Technology.” *Energy Research & Social Science* 12 (February):68–74. https://doi.org/10.1016/j.erss.2015.12.018.

Rep. Yarmuth, John A. [D-KY-3. 2022. *H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022*. https://www.congress.gov/bill/117th-congress/house-bill/5376/text.

Reyna, Janet, Eric Wilson, Andrew Parker, Aven Satre-Meloy, Amy Egerter, Carlo Bianchi, Marlena Praprost, et al. 2022. “U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings.” NREL/TP-5500-83063. National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1877069.

Rogers, Everett M. 2003. *Diffusion of Innovations, 5th Edition*. 5th edition. New York: Free Press.

Ruggles, Steven. 2013. “Big Microdata for Population Research.” *Demography* 51 (1): 287–97. https://doi.org/10.1007/s13524-013-0240-2.

Schmidt, Ruth, and Katelyn Stenger. 2023. "Frame Plurality and 'or/Rationality': A Dialogic Approach to the Behavioral State." *Behavioural Public Policy*.

Sovacool, Benjamin K., and Michael H. Dworkin. 2015. "Energy Justice: Conceptual Insights and Practical Applications." *Applied Energy* 142 (March):435–44. https://doi.org/10.1016/j.apenergy.2015.01.002.

Sovacool, Benjamin K., Mari Martiskainen, and Dylan D. Furszyfer Del Rio. 2021. "Knowledge, Energy Sustainability, and Vulnerability in the Demographics of Smart Home Technology Diffusion." *Energy Policy* 153 (June):112196. https://doi.org/10.1016/j.enpol.2021.112196.

Tawde, Swapnil, Renuka Kamath, and R. V. ShabbirHusain. 2023. "'Mind Will Not Mind' – Decoding Consumers' Green Intention-Green Purchase Behavior Gap via Moderated Mediation Effects of Implementation Intentions and Self-Efficacy." *Journal of Cleaner Production* 383 (January):135506. https://doi.org/10.1016/j.jclepro.2022.135506.

US EPA, OAR. 2023. "Inclusive Utility Investments: Tariffed On-Bill Programs." Overviews and Factsheets. January 13, 2023. https://www.epa.gov/statelocalenergy/inclusive-utility-investments-tariffed-bill-programs.

Walker, Iain, Brennan Less, and Nuria Casquero-Modrego. 2023. "The Costs of Home Decarbonization in the US," December. https://escholarship.org/uc/item/2s4768d2.