Leveraging Digital Twin Analyses to Inform Personalized Customer Engagement for Energy Utilities

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ABSTRACT

As the digital transformation expands across the energy sector, utilities are leveraging AMI-based digital twin insights for supply, power plant, transmission, and distribution planning. Digital twins combine physics-based building models, AMI analytics, and cloud computing to simulate the impact of home energy-efficiency upgrades on an individual household's energy bills and consumption. While utilities regularly use AMI analytics to communicate personalized insights like time-of-day usage and end-use disaggregation, they have less often applied digital twins to provide personalized estimates of savings potential. Even less is known about customer perceptions and behavioral impacts of these predictive insights.

Across two surveys, we explored customer perceptions of digital twin-based insights, including personalized estimates of energy and monetary savings from energy-efficiency upgrades, alongside traditional AMI-driven insights. Customers viewed digital twin insights as moderately valuable, trustworthy, and interesting, and expressed strong interest in receiving them. Compared with other AMI-based insights, digital twin insights were less intuitive but strongly associated with motivation to learn about energy efficiency programs and take energy-saving actions. Mediation analyses showed these effects were driven not by perceived accuracy but by beliefs about the benefits of home upgrades. Digital twin insights were especially motivating for traditionally harder-to-engage customers, including those with lower green identity, lower utility trust, lower email engagement, and greater affordability concerns.

These findings demonstrate that digital twins can meaningfully enhance personalized customer engagement and support effective pathways to energy efficiency program participation.

Introduction

Digital Transformation in the Energy Sector

Utilities are undergoing rapid digital transformation driven by widespread deployment of advanced metering infrastructure (AMI), increased availability of high-resolution customer

energy data, and advances in cloud computing and analytics. AMI adoption has enabled utilities to move beyond monthly billing data toward more granular understandings of electricity consumption across time and end uses. These capabilities have supported a range of operational and planning applications, including load forecasting, distribution system planning, and rate design, while also expanding the tools available for customer-facing energy insights.

In parallel, utilities have increasingly adopted digital twin technologies to support program planning and decision-making. In the residential energy context, digital twins integrate AMI data with physics-based building models and localized assumptions about housing characteristics, equipment, and climate conditions. This approach enables simulation of how specific energy-efficiency upgrades, such as insulation improvements, HVAC replacements, or electrification measures would affect energy consumption and customer bills at the individual household level. Historically, utilities have applied these analyses to inform strategic planning, program design, and portfolio-level forecasting rather than direct customer engagement.

Customer-facing energy communications that have leveraged AMI data, by contrast, have mostly relied on descriptive AMI analytics. Time-of-use visualizations help customers understand when they consume electricity, while energy disaggregation techniques estimate how consumption is distributed across major end uses such as heating, cooling, and appliances. These insights can increase awareness and provide a degree of personalization, but they emphasize past consumption patterns rather than future-oriented, actionable opportunities for savings.

Recent advances in analytics and data integration have created an opportunity to extend digital twin capabilities into the customer engagement domain. By translating complex model outputs into accessible, personalized insights, utilities can shift customer communications from descriptive to prescriptive. Rather than simply showing how energy is used, digital twin-based insights can help customers understand what actions are most relevant for their homes and what outcomes those actions may deliver. This evolution has the potential to strengthen customer energy literacy, remove friction from customer decision-making, and improve alignment between customer motivations and utility energy-efficiency programs.

Despite this potential, customer-facing applications of digital twins remain relatively nascent, and limited empirical evidence exists on how customers perceive and respond to these forms of personalized insights. Understanding whether digital twin–based communications are valued, trusted, and motivating is therefore a critical next step for utilities seeking to leverage digital transformation in support of customer engagement and decarbonization goals.

Digital Twin Technology for Residential Energy Insights

Digital twins in the home energy context. In the residential energy context, a digital twin is a model-based representation of an individual home that combines customer energy data with physics-based assumptions to estimate both current energy use and how that use would change under different upgrade scenarios. Unlike descriptive analytics that summarize historical

consumption, residential digital twins are designed to simulate counterfactual outcomes in terms of what energy use and bills would look like if specific changes were made to the home.

Most residential digital twin implementations begin with AMI interval data, which provide a detailed view of household electricity consumption over time. These data are paired with known or inferred home characteristics, such as building type, size, vintage, heating fuel, and major appliances. When direct customer inputs are unavailable, these characteristics are estimated using building stock data, statistical inference, or comparisons to similar homes. The resulting model is calibrated against observed AMI interval data using established fit metrics aligned with industry standards, such as ASHRAE Guideline 14 benchmarks for acceptable error (e.g., CVRMSE and NMBE thresholds). Model performance is further validated through out-of-sample testing or comparison to measured program savings, helping ensure predicted impacts are directionally reliable even where perfect precision is not achievable.

Once calibrated, the digital twin is used to simulate the impacts of specific energy-efficiency or electrification measures. For each measure, the model estimates changes in energy consumption, peak demand, and customer bills, often accounting for seasonal effects or rate structures. In this paper, the term "digital twin" refers specifically to these individualized, AMI-calibrated residential energy models and the personalized savings and impact estimates they produce.

Comparison to common AMI analytics. A defining feature of digital twins is their predictive, forward-looking nature (Figure 1). While common AMI-based insights such as time-of-day usage or energy disaggregation focus on explaining how energy is used today, digital twins estimate potential outcomes associated with specific future actions.

Commonly, AMI analytics used for customer engagement rely on analytical approaches that lack actionable guidance. For example, time of day usage visualizations are often used to inform customers about their consumption patterns, particularly as an increasing number of customers pay for electricity under time of use rate structures. Similarly, energy disaggregation is frequently employed to present customers with detailed views of their energy consumption. While these approaches can engage customers through customized data presentations, they may fall short of meaningfully improving customer understanding of what actions will most impact their home

When coupled with digital twins, these AMI data analytics can more powerfully engage with customers by delivering personalized content that guides next steps. For instance, digital twin outputs can direct customers toward energy efficiency measures tailored to specific periods of the day. Moreover, by predicting potential savings, digital twin results can emphasize actionable insights—what customers can do to achieve desired energy outcomes—rather than focusing solely on how energy is consumed today.

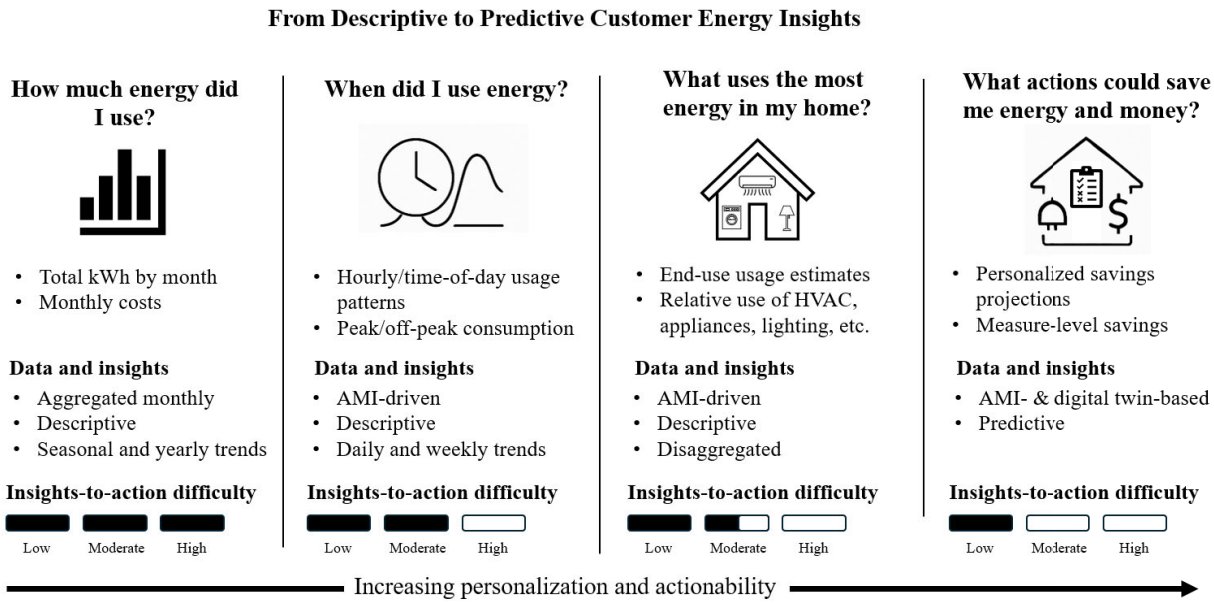

Figure 1. From descriptive to predictive customer energy insights

Potential benefits for customer engagement. Digital twin insights may offer several advantages seeking to strengthen personalized customer engagement and motivate energy efficiency program participation. By providing highly personalized and action-relevant information, digital twin insights can increase the relevance of their communications and help customers more confidently navigate decisions about home upgrades. These forward-looking simulations provide customers with a clearer understanding of which measures are most impactful for reducing their home energy use, helping to reduce the cognitive overload and decision paralysis that often inhibit energy efficiency decision-making (Corradi et al., 2013)

Predictive savings estimates from digital twins can serve as behavioral motivators by translating abstract upgrade benefits into concrete, personalized outcomes. Behavioral science research shows that people are more likely to take energy-saving action when information is personally relevant, easy to interpret, and linked to tangible outcomes (Le-Anh et al., 2023). By quantifying energy and bill impacts at the household level, digital twin insights can reduce perceived uncertainty about the value of home upgrades. This is related to the psychological concept of response efficacy – a person's belief that a recommendation action will be effective at achieving desired outcomes, which is a significant driver of energy-saving action (Rainear & Christensen, 2022; Senooane, 2025).

Research Questions

Our core research questions (RQs) are as follows:

1. To what extent do customers value, trust, and express interest in this type of information? (Study 1 and 2)

2. How do customers perceive digital twin–based energy insights relative to other AMI-driven insights? (Study 1)
3. What potential do digital twin insights have for increasing customer motivation and energy-efficiency program participation? (Study 2)
4. How do perceptions of digital twin insights and potential impacts on motivation and program participation differ across customer segments? (Study 2)

Methods

Study 1

Five hundred single-family homeowners across the U.S. were invited to participate in a study about home energy communications on the recruitment platform Prolific. Participant demographics reflect typical samples from Prolific (Aksoy & Nevo, 2025) and further details are available upon request.

After consenting to participate, participants answered questions about their perceptions of energy-saving actions. They then viewed two randomly presented visuals that displayed AMI-driven insights and were asked to imagine that they reflect information about their home. All participants viewed an image showing average time-of-day usage. Participants were randomly assigned to view an image of either disaggregated energy usage, or digital twin-based insights of personalized energy savings estimates for home upgrades like attic insulation. After viewing each image, participants answered questions about their perceptions and interest in the content shown.

Perceptions. After each image, participants answered **"**If you received this information from your electric utility, how much would you view it as": "Valuable", "Trustworthy", "Interesting", "Helpful" (All on scale of 1, *not at all* to 5, *a great deal).*

Information accuracy. After viewing images on disaggregated energy use and the digital twin-based energy savings, participants answered "On a scale of 0 to 100%, how accurate would you expect this information to be from your electric company?" and "On a scale of 0 to 100%, how accurate does your electric company's estimates of your energy use need to be for you to find the information useful?"

Interest in information. After viewing each image, participants answered "How interested would you be in receiving the type of information you just viewed from your electric company?" (0, *not at all* to 6, *definitely*).

Study 2

Eight hundred and fifty participants were invited to participate in Study 2 using the same platform as Study 1. Participant demographics are available upon request.

Digital Twin-Based Insights. Customers read two descriptions of digital twin-based energy insights – one related to personalized energy savings estimates and the other about personalized monetary savings estimates.

The description of energy savings estimates read: "Electric companies can use smart meter and household data to estimate how much energy your specific home could save from different home improvements. For example, that new attic insulation could reduce your annual energy use by 12-15%."

The description of monetary savings estimates read: "Electric companies can also use smart meter and household data to estimate how much money you could save on energy costs from different home improvements. For example, that new attic insulation could reduce your annual energy costs by $155 - $190."

After each description, participants were asked a range of questions related to their trust, perceptions, and interest in the type of information they read. They were asked the same questions listed in Study 1 plus those listed below.

Interest in information. Participants were asked to indicate what types of energy-efficient home upgrades they would be most interested in seeing personalized savings estimates for, checking all that apply from: air sealing around doors and windows, attic insulation, wall insulation, heating and cooling systems, water heating, lighting, windows, washer/dryer, kitchen appliances.

Energy efficiency upgrades perceptions. Participants were asked on a scale of -3 (strongly disagree) to +3 (strongly agree), the extent to which they agree with the following statements: "*It's worth it to pay for certain upgrades to my home if it means reducing my energy bill*", "*Home upgrades that improve energy efficiency also increase my home's resale value*", "*Home upgrades that improve energy efficiency make my home more comfortable."*

Past utility engagement. To assess participants past engagement with their utility, they were asked "*How often do you open emails from your electric company about ways to save energy?"* (1, *never* to 4, *always*), and "*Have you ever participated in an energy efficiency program with your electric company?*" (Yes, No, I don't know).

Interest in energy efficiency program participation. To assess participants interest in energy efficiency programs they were asked, "*How interested are you in learning about energy efficiency programs from your electric company"* (0, *not at all* to 6, *very interested*),

Behavioral motivation. To assess participants' behavioral motivation "*If you received personalized information on your home energy use based on smart meter and household data, which of the following would you be motivated to do*: *Learn about more ways to save energy, Try new energy saving actions, Open more emails from my electric company, Make energy-saving home improvements, Learn about programs my electric company offers"* (*check all that apply*). Responses were summed to create a behavioral motivation score.

Green Identity. Participants were asked to indicate the extent to which they agree with the following statement (-3*, strongly disagree* to +3 *strongly agree*): "*I think of myself as someone who generally considers the environmental impact of my actions*."

Trust in utility. Participants were asked about the extent to which they agree with three statements about their trust in their energy utility where stronger agreement means stronger trust (-3, *strongly disagree* to +3, *strongly agree*), which were averaged for analyses.

Energy bill affordability. Participants were asked to indicate the extent to which they agree with the following statement (-3, *strongly disagree* to +3, *strongly agree*): "*My monthly electric bill feels reasonable for the service I receive.*"

Results

RQ1: To What Extent Do Participants Value, Trust, and Express Interest in The Information?

Across both Study 1 and Study 2, participants expressed that digital twin-based insights providing personalized energy savings estimates are moderately valuable ($M_1 = 3.35$, $SD_1 = 1.14$; $M_2 = 3.47$, $SD_1 = 1.03$), interesting ($M_1 = 3.32$, $SD_1 = 1.14$; $M_2 = 3.49$, $SD_1 = 1.08$), and trustworthy ($M_1 = 3.58$, $SD_1 = 1.07$; $M_2 = 3.27$, $SD_1 = 1.00$). In Study 1, participants expected that the information would be over 75% accurate while those in Study 2 expected the information would be about 66% accurate. Additionally, in Study 1, participants expressed that the information would need to be around 80% accurate for it to be useful to them while those in Study 2 need it to be around 77% accurate to be useful. Across both studies, participants reported that they would be moderately-to-very interested in receiving this type of information ($M_1 = 5.18$, $SD_1 = 1.81$; $M_2 = 4.13$, $SD_2 = 1.59$) and even more interested if some associated upgrades were provided at no cost ($M_2 = 5.24$, $SD_2 = 1.28$).

Results were similar for perceptions of digital twin-based insights that provide personalized monetary savings estimates. Participants viewed the information as moderately valuable ($M_2 = 3.63$, $SD_2 = 1.05$), interesting ($M_2 = 3.61$, $SD_2 = 1.04$), and trustworthy ($M_2 = 3.33$, $SD_2 = 1.00$). Participants expressed that they expect this information would be around 69% accurate but would need it to be about 79% accurate for it to be useful to them. Interest in this information was moderate ($M_2 = 4.36$, $SD_2 = 1.58$) with stronger interest reported if some associated upgrades were provided at no cost ($M_2 = 5.25$, $SD_2 = 1.28$).

There were no significant differences in perceptions between insights about personalized savings estimates versus monetary savings estimates. However, interest in personalized energy savings estimates was significantly higher than monetary savings estimates ($t(849) = 7.17$, $p < .001$, 95%CI[0.16, 0.29]. Participants indicated what types of energy efficiency upgrades they would be most interested in receiving personalized savings estimates for, with weatherization measures generally showing the strongest level of interest in general (Table 1).

Table 1. Interest in digital-twin based personalized energy savings estimates across specific measures

Type of energy efficiency upgrade	% interested
Air sealing around doors and windows	70.00%
Heating and cooling systems	63.53%
Windows	58.47%
Attic insulation	54.82%
Water heating	49.76%
Lighting	44.12%
Washer/Dryer	43.47%
Kitchen appliances	41.06%
Wall insulation	38.24%

RQ2: How Do Participants Perceive Digital Twin–Based Energy Insights Relative to Other AMI-Driven Insights?

In Study 1, participants viewed images containing time-of-day usage, disaggregated energy use, and digital twin-based personalized energy savings estimates. Compared to time-of-day usage insights, participants viewed digital twin-based savings estimates as less valuable ($t(250) = -7.14$, 95%CI[-0.66, -0.38], $p < .001$), less interesting ($t(250) = -8.45$ 95%CI[-0.76, -0.47], $p < .001$), and less trustworthy ($t(250) = -8.00$, 95%CI[-0.56, -0.34], $p < .001$). Participants also expressed less interest in receiving savings estimates than time-of-day insights ($t(250) = -4.34$, 95%CI[-0.61, -0.23], $p < .001$).

Compared to disaggregated usage insights, participants viewed digital twin-based savings estimates as less valuable ($t(498) = -4.66$, 95%CI[-0.67, -0.27], $p < .001$), less interesting ($t(498) = -4.86$, 95%CI[-0.68, -0.29], $p < .001$), and slightly less trustworthy ($t(498) = -2.43$, 95%CI[-0.41, -0.04], $p = .02$). Participants also expressed slightly less interest in receiving savings estimates than disaggregated usage insights ($t(497) = -2.22$, 95%CI[-0.65, -0.04], $p = .03$).

RQ3: What Potential Do Digital Twin Insights Have for Increasing Customer Motivation and Interest in Energy-Efficiency Program Participation?

To assess the potential impact of digital twin-based insights on customer motivation and energy-efficiency program participation we examined a series of correlations and then explored possible mediational effects of what perceptions might explain relationships between interest in digital twin insights and behavioral motivations and interest in energy efficiency programs.

Table 2 contains correlations among perceptions of digital twin-based energy saving insights, beliefs and motivations around energy efficiency, and behavioral motivation. Most notably, we found that stronger beliefs that digital twin-based energy savings insights are valuable, interesting, and trustworthy are all associated with stronger behavioral motivation to

learn about energy efficiency programs (all *r*s > 0.50, $p < .001$) and interest in greater number of behavioral actions (all *r*s > 0.20, $p < .001$). Interest in receiving digital twin-based energy savings insights is very strongly associated with motivation to learn about energy efficiency programs ($r = 0.81$, $p < .001$). Believing that energy efficiency upgrades are worth the cost to reduce bills, increase home resale value, and improve home comfort were also strongly associated with interest in digital-twin based energy savings insights (all *r*s >.30, $p < .001$), motivation to learn about energy efficiency programs (all *r*s > 0.35, $p < .001$), and interest in a greater number of behavioral actions (all *r*s > 0.15, $p < .001$). We observed the same patterns for digital twin-based monetary savings insights but with slightly stronger correlations across almost all variables.

Exploring possible explanations for the relationships between digital twin-based insights and behavioral motivations. To identify possible drivers of how digital twin-based insights could motivate utility customers to act and participate in energy-efficiency programs, we conducted a series of mediational analyses. These analyses allow us to identify the underlying factors that explain the connection between digital twin-based insights and behavioral outcomes. We ran these analyses using R (v4.5.2) PROCESS model 4 (Hayes, 2022). In this simple mediational model X → M → Y , we use interest in digital twin-based insights as X, behavioral outcomes as Y, and the following perceptions as M: belief that energy efficiency upgrades are worth the cost to reduce energy bills, belief that energy efficiency upgrades increase home resale value, belief that energy efficiency upgrades increase home comfort, and perceived accuracy of digital twin-based insights. These analyses were run for both energy savings digital twin insights and monetary savings digital twin insights. Indirect effects testing the mediational pathways were estimated via bootstrapping (5,000 resamples; bias-corrected 95% confidence intervals).

Table 2. Correlations among perceptions of digital twin-based energy savings insights, beliefs, motivations, and characteristics.

	EE program interest	Behavioral motivation	Interest in receiving digital twin energy savings	EE upgrades - worth the cost	EE upgrades - resale value	EE upgrades - comfort	Digital twin energy savings - valuable	Digital twin energy savings - trust	Digital twin energy savings - interest	Perceived accuracy	Needed accuracy	Trust in utility	Green identity	Bill afford-ability
EE program interest	1													
Behavioral motivation	0.36***	1												
Interest in receiving digital twin energy savings	0.81***	0.36***	1											
EE upgrades - worth the cost	0.43***	0.22***	0.42***	1										
EE upgrades - resale value	0.37***	0.18***	0.34***	0.53***	1									
EE upgrades - comfort	0.41***	0.16***	0.38***	0.57***	0.55***	1								
Digital twin energy savings - valuable	0.61***	0.26***	0.65***	0.41***	0.36***	0.38***	1							
Digital twin energy savings - trustworthy	0.54***	0.23***	0.54***	0.37***	0.34***	0.38***	0.69***	1						
Digital twin energy savings - interesting	0.61***	0.26***	0.62***	0.37***	0.32***	0.36***	0.69***	0.62***	1					
Perceived accuracy	0.50***	0.24***	0.52***	0.35***	0.30***	0.29***	0.47***	0.56***	0.42***	1				
Needed accuracy	0.20***	0.12***	0.26***	0.16***	0.15***	0.16***	0.17***	0.14***	0.20***	0.41***	1			
Trust in utility	0.31***	0.09**	0.30***	0.26***	0.21***	0.23***	0.28***	0.43***	0.34***	0.36***	0.07*	1		
Green identity	0.37***	0.20***	0.34***	0.34***	0.23***	0.34***	0.31***	0.29***	0.32***	0.19***	0.12***	0.20***	1	
Bill affordability	0.14***	0.04	0.14***	0.14***	0.09**	0.10**	0.17***	0.29***	0.20***	0.21***	-0.00	0.59***	0.13***	1

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

Table 3 shows a simple breakdown of which variables were found as significant mediators of the relationship between interest in digital twin-based insights and behavioral outcomes. We found that perceived accuracy of digital twin insights did not explain any relationships between interest in those insights and behavioral. This indicates that, while perceived accuracy is positively associated with interest in digital twin insights and behavioral outcomes, it does not explain the relationship between the two and may not be a core aspect of how digital twin insights can motivate broader behavioral engagement.

Instead, we find that the core drivers of energy efficiency program interest from digital twin-based energy savings insights are participants' perceptions of energy efficiency upgrades. There was a positive indirect effect of believing the energy efficiency home upgrades are worth the cost to reduce energy bills (*ab* = 0.04, 95% CI[0.03, 0.07]), indicating that the influence of digital twin-based energy savings insights on energy efficiency program interest is explained through an increase in the belief that home upgrade cost-effectiveness. Similarly, we see positive indirect effects of the belief that energy efficiency home upgrades increase resale value (*ab* = 0.04, 95% CI[0.02, 0.06]), and increase home comfort (*ab* = 0.04, 95% CI[0.03, 0.06]). This shows that these beliefs also explain how digital twin-based energy savings insights can increase interest in energy efficiency program participation. Looking at broader behavioral motivation, we found that the influence of digital twin-based energy saving insights to motivate a greater number of behavioral actions is explained by the belief that energy efficiency upgrades are worth the cost to reduce energy bills, (*ab* = 0.03, 95% CI[0.01, 0.06]), but not the other perceptions.

We find the same pattern of results for how interest in personalized monetary savings estimates can influence interest in energy efficiency programs – through beliefs that energy efficiency home upgrades are worth the cost to reduce energy bills (*ab* = 0.04, 95% CI[0.03, 0.07]), increase home resale value, (*ab* = 0.03, 95% CI[0.02, 0.05]), and increase home comfort, (*ab* = 0.04, 95% CI[0.03, 0.07]). Similarly, we found that the relationship between interest in personalized monetary savings and broader behavioral motivation was explained by a stronger belief that energy efficiency home upgrades are worth the cost to reduce energy bills, (*ab* = 0.03, 95% CI[0.01, 0.06]), but no other perceptions.

Table 3. Indirect Effect Summary Across Mediation Models

X (Predictor)	M (Mediator) ✓ = Indirect effect supported × = Indirect effect not supported	Y (Outcome)
Interest in digital twin-based energy savings insights	✓ Energy efficiency upgrades are worth the cost to reduce energy bills ✓ Energy efficiency upgrades increase home resale value ✓ Energy efficiency upgrades increase home comfort × Perceived accuracy of digital twin-based energy savings estimates	Interest in energy efficiency programs
Interest in digital twin-based energy savings insights	✓ Energy efficiency upgrades are worth the cost to reduce energy bills × Energy efficiency upgrades increase home resale value × Energy efficiency upgrades increase home comfort × Perceived accuracy of digital twin-based energy savings estimates	Behavioral motivation
Interest in digital twin-based monetary savings insights	✓ Energy efficiency upgrades are worth the cost to reduce energy bills ✓ Energy efficiency upgrades increase home resale value ✓ Energy efficiency upgrades increase home comfort ✓ Perceived accuracy of digital twin-based energy savings estimates	Interest in energy efficiency programs
Interest in digital twin-based monetary savings insights	✓ Energy efficiency upgrades are worth the cost to reduce energy bills × Energy efficiency upgrades increase home resale value × Energy efficiency upgrades increase home comfort × Perceived accuracy of digital twin-based energy savings estimates	Behavioral motivation

RQ4: How Do Perceptions of Digital Twin Insights and Potential Impacts on Motivation and Program Participation Differ Across Customer Segments?

To assess how perceptions of digital twin insights and their associations with motivation differ by customer segments, we conducted a series of regression analyses examining potential interactive effects. We assessed whether the relationship between interest in digital twin-based insights and interest in energy efficiency programs and behavioral motivation differs based on participants past engagement with their utility, concerns about bill affordability, green identity, and trust in their utility.

Results showed that, while the more frequently participants open emails, the more interest they have in energy efficiency programs (b = 0.39, p < .001), the relationship between interest in digital twin-based energy savings insights and interest in energy efficiency programs is stronger among those who open emails less often (b = -0.06, p =.006). Similarly, the more participants view themselves as someone who considers the environmental impact of their actions, the stronger their interest in energy efficiency program participation (b = 0.20, p < .001), but interest in digital twin-based energy savings insights has a stronger influence on interest in program participation among less green participants (b = -0.03, p = .03). There were no observed differences based on participants bill affordability or trust in their utility.

For the potential impacts on behavioral motivation, we found that higher bill affordability concerns are associated with interest in doing a greater number of behaviors (b = 0.16, p < .001) but that interest in digital twin-based energy savings has a stronger influence on behavioral motivation for those with less affordability concerns (b = -0.04, p = .01). We also found that those with a stronger green identity are likely to do a greater number of behaviors the more interested they are in digital twin-based energy savings insights (b = 0.06, p <.001), an opposite pattern from influences on interest in energy efficiency programs. The more participants trust their utility the stronger that interest in digital twin-based energy savings insights influences behavioral motivation (b = 0.04, p <.01).

Similar to results about digital twin-based energy savings insights, interest in monetary savings insights has a stronger relationship to interest in energy efficiency programs among those with lesser email engagement with their utility (b = -0.05, p =.005). Those with higher bill affordability concerns also show a stronger relationship between their interest in monetary savings insights and interest in energy efficiency programs (b = 0.03, p =.002), as do those with lesser trust in their utility (b = -0.03, p = .002). There were no observed differences based on participants' green identity.

For the potential impacts of behavioral motivation, we found that those with a stronger green identity are likely to do a greater number of behaviors the more interested they are in digital twin-based energy savings insights (b = 0.06, p <.001). We found a similar pattern for those with stronger trust in their utility (b = 0.05, p = .006) but observed differences based on participants' email engagement with their utility or bill affordability.

Discussion

This research provides one of the first empirical assessments of how utility customers perceive and respond to digital twin-based energy insights, exploring their potential promise for motivating customer engagement in energy efficiency programs and behaviors. Across two survey studies, we identified key themes with important implications for how utilities can leverage digital twins for customer engagement.

Digital Twin Insights Are Moderately Well-Received but Less Intuitive Than Traditional AMI Analytics

Although digital twin insights were consistently rated as moderately valuable, trustworthy, and interesting, participants in Study 1 evaluated them less favorably than traditional AMI analytics such as time-of-day usage and disaggregation. This suggests that descriptive insights may be more intuitive for customers to process. Digital twin outputs require interpreting forward-looking, counterfactual information, which may be more cognitively demanding than understanding past usage patterns. Many participants likely already receive time-of-day and disaggregated insights from their utility, which would suggest that less favorable ratings for digital twin insights could be from a gap in familiarity rather than a fundamental lack of interest. This highlights an opportunity to optimize framing and visual design to make predictive insights more intuitive. Positioning these insights as a natural extension or in association with familiar AMI-driven insights may help bridge the gap.

Digital Twin Insights May Offer Strong Motivational Benefits

Despite less favorable ratings than other AMI-driven insights, digital twin insights were very strongly linked to self-reported behavioral motivation and energy efficiency program interest. Interest in receiving digital twin insights was more predictive of interest in learning about energy efficiency programs than any other perceptual variable or characteristic. This suggests that while customers may not immediately view this information as more valuable than other descriptive analytics, digital twin insights strongly drive action-oriented thinking. Viewing *what could happen* to one's home may activate a different cognitive pathway than *what has happened,* helping customers overcome a common behavioral barrier of low response-efficacy – the belief that one's actions will make a difference.

This finding is particularly notable given that program participation is often a multi-step process requiring sufficient motivation, perceived relevance, and confidence in potential outcomes. Digital twin insights directly address these psychological needs by providing personalized predictions that help customers envision the consequences of taking action.

The Mechanism Is Not Accuracy of Insights, It Is the Perceived Value of Upgrades

One of the most consistent and possibly surprising findings is that perceived accuracy of digital twin insights does not mediate the influence of interest in those insights on behavioral

motivation or program interest. Instead, the key mechanism is how digital twin insights relate to customers' beliefs about the broader benefits of energy efficiency upgrades like their cost-effectiveness, increased resale value, and added home comfort.

Although customers report that to provide value digital twin insights need to be more accurate than customers perceive them to be, accuracy is not what motivates behavior or program interest. Rather, they need insights that show them energy efficiency upgrades are worthwhile, beneficial, and relevant to their lived experience. Digital twins may be effective because they help customers interpret the value proposition of upgrades in concrete, personal terms. This aligns with evidence from behavioral science that people act when benefits feel meaningful and tailored to them. For utilities, this insight also underscores the importance of emphasizing the "why" behind upgrades and associating predictive savings with messages around broader benefits of home improvements.

Digital Twin Insights May Help Engage Hard-to-Reach or Less Motivated Customers

Several interaction effects highlight the potential for digital twins to motivate hard-to-reach customers. Digital twin insights had stronger influences on self-reported motivation among customers with lower email engagement, lower green identity, higher bill affordability concerns, and lower utility trust. These groups are often difficult to reach through conventional engagement approaches, suggesting that digital twins may have a role in reducing engagement disparities. Personalized, forward-looking insights may feel more directly relevant and actionable to customers with less motivation and fewer financial resources. This aligns with the idea that personalization can reduce perceived friction and increase self-relevance by illustrating that upgrades could directly and meaningfully reduce energy costs and enhance comfort.

Digital Twin Insights May Motivate Broader Action Among Engaged Customers

While digital twin insights may motivate program interest among more disengaged customers, they may also increase broader behavioral motivation (i.e., interest in taking multiple actions) most strongly among customers who are higher in green identity, higher in trust, and more engaged with utility emails. This suggests that digital twin insights have motivational benefits across customer segments in unique ways. For less engaged customers, these insights could act as an initial motivator for program exploration. For already engaged customers, they reinforce and deepen ongoing engagement with the utility. Utilities could take advantage of these unique impacts through tailored messaging – simple benefits-focused messaging nudging toward program participation for disengaged audiences and positively reinforcing messaging nudging toward a broad range of energy efficiency actions for highly engaged customers.

Implications for Utility Program Design

Together, these findings highlight several opportunities for utilities:

1. Pair descriptive and predictive insights, using traditional AMI-driven insights to build familiarity and digital twin insights to motivate action.
2. Simplify and contextualize digital twin outputs, making predictive insights easier to understand and more intuitively connected to customers' lived experiences.
3. Leverage digital twin insights for segmentation, targeting disengaged customers with personalized savings estimates and tailoring messaging to customer priorities.
4. Anchor digital twin insights in broader upgrade benefits given that these beliefs drive program interest more than predictions' accuracy.
5. Prioritize predictive savings high-impact, high-interest weatherization measures.

Limitations and Future Research

This research relies on self-reported behavioral motivations and program interest rather than observed participation. Future work should examine real-world behavioral impacts, including click-through-rates and program enrollment after exposure to digital twin insights. More research is needed to identify potential gaps between stated behavioral intentions and actual program participation. Additionally, perceptions of digital twin insights could vary significantly depending on how the information is presented and through what channels (e.g., email, dashboards). These insights were presented to participants as an image (Study 1) and descriptive text (Study 2) outside the context of a typical utility customer email. Experimental research on framing, visualization, and messaging strategies could help utilities further optimize customer-facing digital twin insights for motivating energy efficiency program engagement.

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