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Play and learn: Serious games in breaking informational barriers in residential solar energy adoption in the United States

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ABSTRACT

Recent literature states the importance of using behavioral science to address the persistent gaps between the technical potential of low carbon technologies and the actual adoption of these technologies. With the goal of addressing this important gap, in this study we investigate the efficacy of *serious games* – games with a primary purpose other than entertainment – to overcome informational and perceptive barriers to broader adoption of solar energy in the residential sector. Using a randomized control trial design with playing a trivia-style game as the treatment condition, we assess the impact of serious games on effecting behavioral antecedents toward solar energy in residential energy customers, applying the Theory of Planned Behavior (attitudes, norms, and perceived behavioral control). Our findings indicate that serious games are effective in bridging the information gap and enabling participants to feel agency, warranting further investigation of the effectiveness of this intervention strategy on behavioral change applied at large scale.

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1. Introduction

The adoption of solar energy – widely assumed to be pivotal to a new energy transformation – has been hindered by persistent information gaps [1–8]. However, providing information alone has not proven sufficient to bridge information gaps or motivate behavior change [9–11]. Here we explore a different approach – known as "serious games" – in which participants actively engage with actionable information presented through a game interface, in this case a trivia-style game. Using a randomized control trial (RCT) design we assess the potential of serious games (i.e., games with a primary purpose other than entertainment) to influence the antecedents of behavior, attitudes, norms, and the perception of control, as set forth in the Theory of Planned Behavior (TPB), which then impact intentions and behavior [12], toward solar energy among residential energy customers.

Technically complex knowledge areas such as solar energy are easily misunderstood [5,13–16]. Additionally, the motivations of potential solar adopters continue to evolve [17,18], which increases the need for communication methods that can target multi-dimensional information gaps for diverse customer base. Thus solar adoption serves as a compelling test bed, due to its complex nature as an innovative, capital-intensive, and pro-environmental durable good. When deciding whether to adopt solar customers need to process a range of information in a decision-making context that includes the interplay of social, behavioral, economic, and technological factors. But information alone is not sufficient [8,9,19] to change public perceptions, address inaccurate anchoring, or correct misunderstandings and prematurely formed conclusions common to residential energy use [5,6,20]. Providing information in a passive or static format allows for overlooking differences with existing perceptions or for confirmation bias (the tendency to interpret information to confirm preconceptions). Furthermore, according to the "ostrich effect" pointed out by Karlsson et al. [21] information may be avoided entirely if an expectation of negative information exists, such as a *perception* of unaffordability for solar [7]. Thus correcting misperceptions may require a different approach to communicating information when the aim is to correct misunderstanding, deter confirmation bias, circumvent the ostrich effect, or address inaccurate anchor points [22,23]. Serious games offer a holistic approach for addressing such complex decision contexts marred by information gaps, as they can confront misperceptions, reduce information search costs, and challenge multi-dimensional information gaps, all known barriers to the adoption of solar energy.

The study presented here is intended to advance the understanding of the potential of serious games to bridge information

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gaps by first determining if serious games are useful and impactful in the context of bridging information gaps in solar energy. While the benefits of gamification can be specific to the game design and mechanics, which, having many facets (e.g., motivational affordances, subject matter, game genre, audience), makes generalization of game results difficult [24,25], the impact of specific game design elements is beyond the scope of this study. To mitigate the confounding factors associated with game design elements, as further discussed in Section 3, we have selected a relatively simple, straightforward game design (compared to designs such as multi-level, simulation, virtual world, etc.). Thus our findings relate to the impact of the relatively simple game we use in our experiment – a trivia-style game involving a few game elements – rather than to the differential impact of the individual game elements themselves. Within that context, our findings support the potential of serious games to bridge information gaps and enable participants to feel agency. Thus, applied at a large scale serious games could prove effective in activating the passive customer base, helping unlock emissions reductions in the residential sector.

2. Background and related literature

In contrast to providing information through "passive" channels (such as through pamphlets or e-flyers), a more interactive approach to presenting information, such as via a trivia game, could potentially challenge misperceptions and prompt reexamination of the original content [26–28]. The interactive nature and motivational affordances provided by a gamified platform [29] could provoke the reassessment of solar energy necessary to bridge information gaps, establish accurate anchor points, and increase agency in conservation and solar adoption decisions. However, there have been few systematic studies along these lines, particularly with regard to behavior change and non-student populations [26,30].

Connolly et al. [26] identify only twelve RCTs in their review of computer games and serious games studies related to learning, skill enhancement, and engagement. Of these twelve studies, six focused on knowledge acquisition, only one focused on behavior change, and none of these addressed energy topics. A 2016 update of this review using the same methodology identifies an increase in the quality and number of studies related to serious games [31]. Silk et al. examined the effectiveness of multiple modes of communication to impact nutrition education [32]. In that study, website and game modalities faired best on attention, and the website ranked highest among the modalities for attention, understanding of content, learning, and intent to use for additional information. Silk et al. note that the results may be indicative of the audience preferences and the appropriateness of the game to the domain of the study. Additionally, the design and quality of a game can be instrumental to an intervention's success [33–35]. These are important points because given the potential costs of game interventions matching the game design to the population and domain of interest may be necessary to maximize the benefits of game based interventions.

In the energy domain a number of studies have used games to target energy efficiency behavior. Orland et al. implemented an RCT in the workplace using sensors to measure and provide feedback through a game interface with short-term reductions in energy consumption, but these energy savings did not persist in the eight weeks following game play [36]. An RCT study using a commercial quality game developed by Reeves et al. proved effective in reducing energy use among college students by 2%, but the savings did not persist in the 30-day follow-up [35]. Gustafsson et al. found both increased energy efficiency behavior and increased attitude toward energy efficiency, but the significant difference between game and control groups declined shortly thereafter [37]. The effectiveness of games in reducing energy consumption is encouraging; however, the lack of persistence presents a challenge for ongoing behavior change. These results suggest that such interventions may prove more effective with one time behaviors, such as solar adoption, that do not need to be repeatedly sustained beyond the adoption. Here we study the use and effectiveness of online serious games due to their unique ability to combine information delivery, real-time feedback, and normative cues, which are each effective intervention strategies for catalyzing behavior change [10,26,38–41]. To assess the effectiveness of serious games in this context, we investigate the influence of serious games to act on the antecedents of intentions and behavior as set forth in TPB.

The TPB model is frequently applied to understand energy-related behavior, pro-environmental behavior, and sustainable choices [3,42–47]. TPB identifies three antecedents of *intentions* to perform a behavior: *attitudes* toward the behavior formed from behavioral beliefs – beliefs about the likely outcomes of a behavior and the evaluations of those outcomes; *subjective norms* formed from the normative expectations of others and motivation to comply with such expectations; and *perceived behavior control* (PBC) based on beliefs regarding factors that may enable or hinder the behavior [12,48]. The behavioral intention, thus formed, and PBC then directly impact *behavior*.

In a meta-analysis of nearly 200 TPB studies across many applications (education, health, energy, etc.), Armitage and Conner [49] found that 39% of variance in intention and 27% of variance in behavior could be explained through TPB. A meta-analysis specifically on pro-environmental studies also finds that 27% of variance in behavior can be accounted for by TPB, and that 53% of intentions are accounted for by PBC, attitude, and moral norm [44]. Furthermore, a recent meta-analysis of interventions based on TPB finds a mean effect size of 0.50 for changes in behavior and effect sizes ranging from 0.14 to 0.68 for antecedents of behavior [50]. Bamberg et al. [42] leverage TPB to evaluate the effectiveness of a behavioral intervention on travel-mode choice, a pro-environmental behavior, adding past behavior as an additional antecedent of future behavior [42]. They find past behavior has limited effect on future behavior when the conditions or context of the behavioral decision change. This is particularly relevant to technologies such as solar for which changing economics (e.g., declining prices, changing electricity prices, and new business models) and technological advancement (e.g., higher efficiency, greater reliability, and product integration) are consistent features of the landscape. Effectively communicating this changing context to potential adopters becomes critical in the decision-making process to adopt or reject a technology as it evolves.

3. Methods

In order to impact the behavioral antecedents and consequently the intentions and behaviors toward adoption of solar energy that follow, we designed the game content to specifically address the attitudinal, normative, and control factors in the TPB framework.[1] The experimental design includes: (1) a pre-game survey to capture measures of existing TPB constructs (attitudes, norms, and PBC), intentions, and behaviors, (2) a two-week gap for the treatment cohort ("game cohort") to play *Energy Games*, a real-time trivia game based on the Ringorang® platform, and (3) a post-game survey to capture changes in those same TPB constructs, intentions, and behaviors. The post-game survey was launched immediately following the game to reduce attrition and the chance of exposure to other sources of information, which would make causal

[1] As noted below in Sections 3.1 and 5, this study does not include analysis of behavior change, but rather focuses on the antecedents and intentions that lead to behavior change.

identification more difficult. The control cohort was not contacted during the time between the two surveys. The game platform, further described in Section 3.3, was selected for its customizability (for content), intuitive user interface, and straightforward game play design (compared to designs such as multi-level, simulation, virtual world, etc.). As more game elements are included, attributing impacts to the interactive nature of the game, rather than specific game elements, becomes increasingly challenging, thus selecting a minimal set of game elements mitigates potential confounding factors associated with game design elements. Another implication of a relatively simple game design is that to the extent we find significant effects scope exists to induce additional effects by leveraging additional or more advanced game elements (e.g., goal setting, repetition, customization).

3.1. Survey instrument

The survey instruments were developed according to guidelines for developing a TPB questionnaire [45,51] using a 7-point Likert scale with "Agree" written beside 7 and "Disagree" written beside 1, unless otherwise noted. Intermediate ratings were labeled numerically. The pre-game survey included demographic information, in addition to questions used to assess the TPB constructs, intentions, and behaviors related to solar energy adoption, as well as energy conservation (discussed in Section 3.3 below), which were included in both surveys. The same process was used to construct variables for both pre and post surveys.

Solar attitude is divided into two components: financial and environmental. The financial attitude construct is an index variable calculated as the mean of multiple questions regarding saving money, long term investment, and increasing home value. The environmental attitude component consists of a single question on environmental benefit. Subjective norms stem from the normative expectations of others and motivation to comply with those expectations, which are measured by asking, "If I install a solar system on my roof, people who are important to me would approve." The case we are interested in – the behavior of installing solar – has a visible result in the typical residential home – solar panels mounted on the roof. Additionally, this is a one-time action, unlike recurring behaviors. The singular and visible nature of this behavior simplifies the measurement of the relevant subjective norms. By specifying people who are "important," we also include the motivation to comply [42,45]. There are a number of factors contributing to PBC, such as perceptions of affordability and suitability of physical factors (e.g., roof area, tree cover, irradiation). However, the high initial cost of solar has emerged in the literature [14,52,53] as a dominant factor in solar adoption and decision-making, which can be effectively addressed through Energy Games content. The physical factors on the other hand are site specific and cannot be readily addressed without more information. Thus we focus on the affordability factor, measuring PBC based on the statement, "A solar system is affordable for my household." To measure intentions, the pre-survey asks participants to rate the likelihood of calling a solar installer for a quote. To further clarify intentions given the positive attitude of respondents (discussed further in Section 4), in the post-survey we added a time frame in the measure of intentions: respondents were asked to rate the likelihood of calling a solar installer for a quote "some time in the near future." Given the low penetration rate of solar in the study area, behavior was measured by asking, "Have you ever called a solar installer for a quote?" We note that this behavior is an intermediate behavior leading to the final behavior of actually adopting solar, which we do not address due to the short study period (discussed further in Section 5). Further discussion of survey development and all survey questions are available in the Supplemental information Section 1.1.

We used a direct mail (postcard) campaign to recruit respondents to the pre-game survey. Single-family residences were randomly selected in three cities in Texas: Corpus Christi (2013 population: 316,381), Abilene (2013 population: 120,099), and San Angelo (2013 population: 97,492) [54]. These cities were selected based on three criteria: (1) areas with significant solar incentives, (2) urban areas, and (3) competitive retail regions of Texas (see Supplemental information Section 1.2). All respondents were offered a $10 Amazon gift card and entry into a prize drawing for one $500 and two $150 Amazon gift cards. These incentives were separate from the incentives offered in the game, which were not mentioned in the initial outreach.

After completing the pre-game survey, the respondents ($n = 522$) were randomly assigned to either the control ($n = 150$) or the game cohort ($n = 372$), with a greater assignment to the game cohort to account for the additional attrition points expected in response to an email invitation to play and the need to download the game. The assigned cohorts showed no significant difference in demographic variables or in geographic distribution across the three cities ($\chi^2(2, 100) = 2.39$, $p = 0.30$). The control cohort received no further contact until the post-game survey, which had a 50% return rate ($n = 76$). The game cohort was invited via email to participate in the game. The response rate to the email invitation was just over 15% ($n = 60$), which is a typical response rate for this type of communication [55]. Of those 60, 30 downloaded and actively played the game, with a 90% response rate on the final survey ($n = 27$). The high response rate to the final survey among those who played the game confirms that the results are representative across all game participants and not biased towards only those who chose to complete the final survey. The participation rate in the game was 85%, calculated as the total number of questions played by all participants divided by the total number of questions available to all participants. The average player spent a total of 22 min of contact time over the two-week duration.

3.2. Sample bias

We took a number of steps to minimize selection bias, which to some degree is inevitable in the context of voluntary participation in any experiment [56]: 1) the recruitment campaign randomly targeted a representative sample of residents in the selected area; 2) the initial recruitment for the game, i.e., the postcard, made no mention of solar; 3) the cohorts were assigned randomly amongst respondents to the pre-game survey; 4) the resulting cohorts, i.e., participants that completed the final survey, were demographically comparable; and 5) the final cohorts were comparable across nearly all initial TPB constructs (exceptions noted in the next paragraph). To point 4 above, a difference of means test between the control and game cohorts showed no significant difference in age, gender, educational attainment, or income (see Supplemental information Section 1.3). Thus, overall, our RCT design appears to have been quite effective.

The control and game cohorts differed on solar environmental attitude, a TPB construct, (6 for control cohort and 6.7 for game cohort, on a 7-point Likert scale)[2] and on incentive awareness. To test the effect that solar environmental attitude and incentive awareness might have on PBC and intentions – the two main outcomes of interest in this study (see Section 4) – we ran a series

[2] Respondents to the initial survey that were invited to play energy games did not differ significantly from the control group, but differed from those who elected to play along the same metrics and in the same way as the control cohort. Thus the following discussion of bias between the game and control cohorts also applies to those who were invited versus those who elected to play, i.e., attrition among the game invitees.

of regression models and found neither solar environmental attitude nor incentive awareness to be significant predictors of PBC or intentions for either cohort. This gives us confidence that the initial differences between cohorts on solar environmental attitude and incentive awareness are not driving the main results we report in Section 4. Furthermore, since attitudes are a behavioral antecedent within the TPB framework, we control for initial solar environmental attitude in the repeated measures ANOVA discussed in the results presented in Section 4, to further mitigate any possibility that the initial difference between cohorts for solar environmental attitude is driving our main results.[3]

Our RCT design enables us to directly overcome the three most significant sources of bias (in terms of magnitude) commonly found in energy pilot studies (see Table 2, p. 404 in Davis et al. [56]): *intervention selection bias* (subjects select which experimental condition to receive), *sequence generation bias* (cohort generation depends on certain conditions at successive stages of the experiment, violating strict randomization principles), and *allocation concealment* (subjects or experiments selectively use knowledge of assignment sequence to match assignment to condition.) We also believe that our experiment does not suffer from *blinding bias*, whereby experimenter or subject knowledge of the experimental condition produces effects unrelated to the treatment condition. To the best of our knowledge, at no point did our specific knowledge of control vs. game condition lead to a selective interpretation, i.e., we used the same data collection and analysis approach, including variable definitions and models, when analyzing both control and game cohorts. Furthermore, we are able to mitigate any blinding bias potentially resulting from subjects through using multiple, subtle outcomes (for example, TPB constructs of attitude, norms, and PBC) not overtly related to the main outcome of interest (calling a solar installer for a quote). Additionally, subjects were not aware of the main outcome of interest to us. Finally, as discussed above, while we do have attrition among game invitees that does not lead to *attrition bias* – whereby subjects withdraw from the study due to reasons related to the assigned experimental condition – in our findings. Overall, our careful experimental design and implementation together with multiple robustness checks give us strong confidence that our findings are robust to the most debilitating sources of bias commonly encountered in experimental studies involving human participants.

3.3. Game design and content

The Ringorang® platform [57] is a real-time trivia game, with customizable content, available for smartphones and desktop computers. Questions are presented in an interactive sequence that includes a clue, followed by a question and multiple-choice answer options. While the results are computed in real-time, players are presented an insight that elaborates the subject matter with an optional link for additional information. The app then reveals the correct and incorrect answers. The questions were arranged into themes lasting one week and including 15 topical questions (five questions per day, three days a week). Overall, Energy Games lasted for two weeks and entailed 30 questions total; each week covered both solar energy and energy conservation content (see Supplemental information Section 2.1 for more details).

The content of Energy Games included both solar energy and energy conservation and efficiency information. The solar energy literacy content included benefits/costs, leasing, incentives, and general solar literacy. Energy conservation was included for three reasons: 1) to reduce self-selection bias by including information relevant to all homeowners, not just those interested in solar, 2) to provide an additional dimension on which to evaluate the impact of Energy Games, and 3) to create an integrated solar energy and energy conservation curriculum to support the practice of conservation first to right-size solar installations (see Supplemental information Section 2.2 for complete content). To develop the energy conservation content for Energy Games, we adapted Gardner and Stern's "short list" of the most effective energy curtailment and efficiency tools to Texas [58]. The content for both topics focused on objective information and potential benefits and concerns to consider in the decision-making process (e.g., solar leasing is available; focus energy conservation on areas where you use the most energy), rather than emotional appeals or brand endorsements typical of marketing.

The content was developed to present information that directly addressed attitudes, norms, and PBC. The Energy Games content addressed attitudes through reinforcing the favorable cost, benefit, and risk assessment of solar energy [43]. We addressed norms by presenting statistics such as the increase in solar installations and the average energy expenditures on certain items. Finally, PBC was addressed through actionable information items, such as optimal thermostat temperature settings or solar leasing options, supported by links to utility incentive programs and informational "DIY" videos for home energy conservation improvements (e.g., how to caulk windows, add weather stripping, insulate a water heater). Two independent researchers (one of the authors and another researcher versed in TPB) evaluated the content of the questions to determine the frequency with which each TPB construct was addressed. Information related to PBC was addressed the most frequently, in just over 70% of the questions, followed by attitudes (~55%), and norms (~20%). Due to the limited content on norms, the emphasis of our analysis is on attitudes and PBC. (note: these sum to over 100% as some questions addressed multiple constructs).

4. Results

A prior analysis of the pre-game survey included regression models using attitudes, subjective norms, and PBC as predictors of intentions and using intentions and PBC as predictors of behavior, according to TPB [7]. For solar, no participants had installed solar (a behavior), thus we focused on measures of intentions, specifically, the likelihood of calling a solar installer for a quote. In TPB models, attitude and PBC were significant predictors, with PBC having the strongest influence. An additional key finding of that analysis was that customer awareness of the cost of solar photovoltaics (PVs) has not caught up with available incentives and rebates, declining prices, and lease options that are quickly increasing the affordability of solar PV, leading to the perception that solar PV is unaffordable.

For energy conservation, all three TPB constructs were significant predictors of intentions, and intentions and PBC were both significant predictors of behavior. As with solar, PBC emerged as the strongest predictor of both intentions and behavior for energy conservation (see Supplemental information Section 3). Accordingly, the ability to impact PBC through Energy Games is of particular importance, given that PBC shows consistent influence across all models and influences behavior both directly and indirectly as an antecedent of both intentions and behavior. Thus the strongest possible support for the assertion that serious games can effectively address information gaps and catalyze behavior change would be

[3] A likelihood ratio test between TPB models of intentions including and not including initial solar environmental attitude indicates that the model including initial solar environmental attitude is a better fit, accounting for 1.5% of variance (Chi-square(1) = 1.58, p = 0.0), though the initial solar environmental attitude variable is not significant (b = −0.14, p = 0.21).

if Energy Games significantly impacts both PBC and intentions, the antecedents of behavior.

Table 1 shows the mean and standard deviation by cohort for the pre- and post-game surveys and the change between the two surveys. To quantify the changes in TPB constructs following Energy Games, we used a repeated measures ANOVA, with cohort (control or game) as a between subjects variable and time (pre and post) as a within subjects variable, with post hoc pairwise comparison, as shown in Table 2. Solar financial attitude changed positively for the game cohort compared to the control ($\Delta = \overline{\Delta x_{game}} - \overline{\Delta x_{control}} = 0.34$), but the change was not significant (p = 0.22). The two cohorts differed significantly on environmental solar attitudes (Δ = 0.7, p = 0.02) initially, but neither cohort showed any change over the course of the experiment (p = 0.96). More importantly, PBC differed significantly between the cohorts over time (Δ = 1, p = 0.001) with a moderate to large effect size, Cohen's d of 0.71 [59].

Looking at changes in intentions, while controlling for solar environmental attitude, the likelihood of calling a solar installer for a quote increased significantly for the game cohort compared to the control over time (Δ = 0.68, p = 0.01), with a moderate effect size, d = 0.49. The control cohort saw a significant *decrease* in response to this question (Δ = −0.37, p = 0.03,), likely due to specifying a shorter time frame in the post-game survey. In the pre-game survey the question asked, "How likely is that you will call a solar installer for a quote?" In order to better assess how immediately an information campaign might make a difference in adoption, the question was changed in the post-game survey to, "How likely is it that you will call a solar installer for a quote some time in the near future (within the next few months)?" That the response from the control cohort decreased significantly indicates that the intentions measured in the pre-game survey were more aspirational, whereas the shorter time frame captures more imminent intentions.[4]

In addition to intentions and behaviors regarding solar energy, we also measured awareness of solar incentives. In the pre-game survey, only 15% of respondents were aware of solar incentives, despite living an area with a $1.20/Watt incentive in addition to the 30% Federal Investment Tax Credit. Awareness of incentives increased significantly for the game cohort compared to the control (p = 0.005) with a change in awareness of incentives 10 times greater than for the control cohort over the same time period. Given our prior findings [7] on the outdated perceptions of the financial aspects of solar, the ability to increase the awareness of incentives is encouraging for serious games as an effective information channel for consumer solar energy education. However, further study would be necessary to determine if and when serious games are more effective than standard information channels for increasing incentive awareness.

Though not the primary focus of this study, the energy conservation content provides an additional energy related context on which to assess the impact of Energy Games. Energy conservation attitude in the game cohort showed a significant change relative to the control over time, p = 0.04 (Δ = 0.49), with a moderate effect size, d = 0.46. Most importantly, PBC increased significantly for the game cohort compared to the control over time (Δ = 0.57, p = 0.02) with a moderate effect size, d = 0.53. Since PBC was the single most significant predictor of intention and behavior, as discussed above, the ability to positively impact PBC through Energy Games shows that serious games can be an effective intervention strategy. Furthermore, when asked about the likelihood of calling an energy auditor in the near future,[5] the game cohort stated a significantly greater intention to do so (Δ = 0.77, p = 0.03) with a moderate effect size, d = 0.48. Increasing the uptake of energy audits is particularly valuable, since audits are a point of entry to implementing a wide range of energy improvements with the benefit of expert advice on the most effective site-specific improvements. Achieving these improvements in PBC and intentions for energy conservation in addition to solar energy provides direct supporting evidence of the robustness of results for serious games as a useful tool for bridging energy information gaps.

5. Discussion

Energy Games consistently proved effective at impacting PBC and intentions, the antecedents of behavior, for the adoption of solar PV. Solar PBC started at a low value (3.07) before Energy Games, thus raising it above the neutral point (4 on a 7-point scale) to 4.07 is particularly important for instigating solar adoption, presuming that those with neutral or higher PBC will be more receptive and attentive to new and changing information than those who firmly believe that solar is beyond their reach. For solar intention, both the control and game cohorts had indistinguishable responses to the initial question (without any specific time frame for adoption) on the pre-game survey (p = 0.77), but the game cohort was significantly higher compared to the control on the post-game survey question on intention to adopt "within the next few months" (Δ = 0.79, p = 0.03). This suggests that serious games have the potential not only to positively influence intentions, but also to compress the time frame for adoption. Thus for solar, we see a significant impact on both PBC, the single most significant construct influencing the likelihood to request a quote for solar, and intention, suggesting that serious games show promise as an effective intervention approach. Further study with a sufficient sample size to account for attrition will be necessary to determine if these increases in behavioral antecedents are sufficient to impact solar adoption behavior, but these initial results provide encouraging support for proceeding with larger scale studies.

While our experiment did not specifically test for this, we suggest that the effectiveness of Energy Games is likely due to a combination of three factors. First, the trivia-style game *confronts misperceptions* by requiring that players definitively choose an answer and then receive clear, immediate feedback of whether they are correct, rather than more passive means of receiving information (e.g., a pamphlet or newsletter) that leaves the content vulnerable to confirmation bias or the ostrich effect [21]. Second, by providing distilled, actionable information Energy Games *reduces information search costs*, a recognized barrier to solar adoption [8,60], since the average participant only spent a total of 22 min playing the game to achieve significant gains in PBC and intentions. Third, Energy Games *challenges multi-dimensional information gaps* by chipping away at a broad scope of dimensions, such as attitudes, norms, costs, benefits, and performance. Such combined effects are known to be effective in inducing energy-related behavior change [9]. Confirmation that these mechanisms are causative for the exact nature of the effectiveness of Energy Games will require additional study, as this study sought primarily to demonstrate effectiveness, rather than the mechanism(s) of effectiveness.

Furthermore, that PBC was addressed most heavily in the game content and also exhibited the most significant change among the antecedents of game participants, while attitudes had middling

[4] Given the change in question wording, we also looked at a *t*-test comparing only the post-survey response between the control and game cohorts, which shows a significant difference (p = 0.03) and similar (and slightly larger) effect size to the repeated measures ANOVA (d = 0.52).

[5] The pre-game survey did not include intentions toward getting an energy audit, only whether participants had gotten an audit (a behavior). This question was added to the post-game survey and is discussed further in the Supplemental information Section 1.1.

Table 1

Mean and standard deviation in parenthesis for the pre-game survey, post-game survey, and the difference between the means ($\Delta = \overline{\Delta x_{post}} - \overline{\Delta x_{pre}}$) for the control (n = 76) and game (n = 27) cohorts.[a]

	Control			Game		
	Pre	Post	Δ	Pre	Post	Δ
Solar Energy						
Attitude_finance (α = 0.92)	5.14	5.26	0.12	5.83	6.28	0.46
	(1.82)	(1.56)	(1.14)	(1.45)	(0.88)	(1.37)
Attitude_environment	6.01	6	−0.01	6.7	6.7	0
	(1.52)	(1.51)	(1.23)	(0.54)	(0.67)	(0.68)
Subjective Norms	4.96	4.83	−0.13	5.52	6.04	0.52
	(1.87)	(1.59)	(1.32)	(1.7)	(0.98)	(1.76)
Perceived Behavioral Control	3.17	3.03	−0.14	3.07	4.07	1
	(1.67)	(1.62)	(1.27)	(1.57)	(1.66)	(1.88)
Intentions Quote	3.09	2.71	−0.37	3.19	3.50	0.31
	(1.47)	(1.5)	(1.39)	(1.49)	(1.58)	(1.38)
Behavior Quote[b]	9/67	9/67	0	1/26	2/25	1/26
Incentive Awareness[b]	18/58	20/56	2/74	1/26	7/20	6/21
Energy Conservation						
Attitude	5.63	5.45	−0.18	5.63	5.94	0.31
	(1.1)	(1.12)	(1.18)	(0.83)	(0.74)	(0.65)
Subjective Norms	5.07	5.10	0.03	5.33	5.56	0.22
	(1.53)	(1.41)	(1.14)	(1.23)	(1.35)	(1.23)
Perceived Behavioral Control	5.31	5.26	−0.05	5.39	5.91	0.52
	(1.27)	(1.2)	(1.16)	(1.1)	(1.02)	(0.79)
Intentions_auditor[c]		3.19			3.96	
		(1.61)			(1.56)	
Behavior_auditor[b]	9/67	11/65	2/74	6/21	6/21	0

[a] Pre- and post-game survey questions were on a 7-point bipolar (Agree/Disagree) Likert scale. Cronbach's alpha in parenthesis.
[b] Binomial data shows Yes/No for pre and post and Change/No Change for Δ.
[c] Variable only measured on post-game survey.

Table 2

Repeated measures ANOVA shows results for between cohorts ("Cohort"), between the pre- and post-survey ("Time"), and for the interaction between the two ("Cohort × Time"). The post hoc column shows the post hoc pairwise comparison between control and game cohorts for the pre-survey (labeled "pre") to denote whether cohorts differed initially on the pre-survey and the pre- and post-survey change ("post-pre") when the Cohort × Time interaction was significant.

		Cohort		Time		Cohort x Time		Post hoc
		F	p	F	p	F	p	p
Solar Energy								
Attitude_finance	ANOVA	6.85	0.01*	4.61	0.03*	1.53	0.22	
	pre							0.08
Attitude_environment	ANOVA	6.52	0.01*	0	0.96	0	0.96	
	pre							0.02*
Subjective Norm	ANOVA	7.01	0.01*	1.42	0.24	4.02	0.05*	
	pre							0.18
	post-pre							0.05*
PBC	ANOVA	2.10	0.15	6.90	0.01*	12.36	0.001*	
	pre							0.79
	post-pre							0.001*
Intentions – Quote	ANOVA	0.44	0.51	4.0	0.05*	6.86	0.01*	
	pre							0.49
	post-pre							0.01*
Incentive Awareness[a]	pre							0.02*
	change							0.005*
Energy Conservation								
Attitude	ANOVA	1.51	0.22	0.33	0.57	4.23	0.04*	
	pre							0.99
	post-pre							0.04*
Subjective Norm	ANOVA	1.54	0.22	0.96	0.33	0.53	0.47	
	pre							0.18
PBC	ANOVA	2.30	0.13	3.86	0.05*	5.51	0.02*	
	pre							0.77
	post-pre							0.02*
Intentions_auditor[b]	post							0.03*

[a] Yes/No response. Fisher's exact test to compare change between cohorts.
[b] Difference of means test only, since initial survey did not include this question; further discussion in Supplemental information Section 1.1.
* Indicates $p < 0.05$.

changes and norms (least heavily addressed in game content) had the least change, indicates that the impact of Energy Games is directly related to the composition of the content. This observation gives us further confidence that our results do not suffer from blinding bias (see Section 3.2), i.e., the treatment condition (Energy Games), not simply the awareness of receiving the treatment, is driving the outcomes. This also suggests that Energy Games may offer a flexible mechanism for targeted intervention by varying the proportion of the content. Additionally, we note that influencing PBC, a direct antecedent to both intentions (an immediate antecedent of behavior) and behavior, will likely have an amplified impact on behavior [12].

We note two limitations in our study. First, while the randomization was largely successful (see Section 3.2), with the control and game cohorts comparable on all key demographics and nearly all TPB constructs, it was not perfect in that the final cohort composition differed on initial solar environmental attitude and initial incentive awareness. The stronger environmental attitudes could be a motivating factor in choosing to play Energy Games, compared to those who were randomly invited to play but chose not to. However, as discussed in Section 3.2, multiple model checks confirmed that initial differences between the cohorts are not driving our main conclusions; further, we also controlled for solar environmental attitude in the final analysis estimating game effects on intentions. Additionally, solar environmental attitude did not change over the course of the experiment for either group (Table 1), further minimizing the potential for bias. While sources of bias are inevitable for voluntary participation, the control group plays an important role in demonstrating that the survey alone did not instigate independent research or changes in the antecedents of interest (i.e., the Hawthorne effect) [56,61,62]. Conceivably, the survey or participation in a research study could have instigated independent research into solar energy, which could change the behavioral antecedents. Had this been the case, we would expect to see a change in the control cohort; that the control cohort had no significant changes in the TPB antecedents (excepting the decrease in intentions in response to an intentional change in question phrasing) or incentive awareness strongly supports that changes seen in the Energy Games participants are related to the game only. Second, given the short duration of the study, measuring actual behavior change was intractable, since it takes longer than two weeks to obtain a solar quote and eventually install solar. Thus, our study focused on measuring changes in significant *antecedents* of behavior, in particular, PBC and intentions. We believe this approach provides valuable insight into the capabilities of using serious games in intervention programs to influence behavior change, though further work will be needed to directly assess behavior change, such as the durability of results, actual uptake of solar following the intervention, and broad public appeal to participate in such an intervention.

6. Conclusion

The untapped potential of solar energy, which is pivotal to a new energy transformation, prompted this research into serious games as a behavioral intervention approach. We conducted an RCT with a non-student sample using a pre- and post-game survey instrument to assess changes in the TPB antecedents (attitudes, subjective norms, and PBC) and intentions toward solar energy, as well as incentive awareness and energy conservation, resulting from playing Energy Games (a trivia-style game). Our prior in-depth analysis of the pre-game survey results reveals the influence of the TPB antecedents and the emergence of PBC as the single most important variable across all models for both solar energy and energy conservation. Thus, that Energy Games significantly and consistently increased PBC and intentions for both solar energy and energy conservation supports the effectiveness of serious games in addressing information gaps and facilitating energy-related behavior change. Since Energy Games utilizes a relatively simple game design, more advanced and complex games that effectively leverage various game elements may provide even larger impacts. Overall, by effectively addressing information gaps, serious games, such as those embodied in Energy Games, show promise in helping participants feel agency and may "activate" the passive potential customer base for unlocking emissions reductions in the residential sector.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.erss.2017.03.001.

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