Current Sustainable/Renewable Energy Reports
https://doi.org/10.1007/s40518-018-0106-8

END-USE EFFICIENCY (Y WANG, SECTION EDITOR)

Feedback and Behavioral Intervention in Residential Energy and Resource Use: a Review

Stephen Bird[1] · Lisa Legault[1]

Abstract

Purpose of Review A proliferation of research has emerged in the last 20 years, and especially in the last 5 years, on how to effectively engage inhabitants in energy and resource saving behaviors in the residential context. Such conservation behavior is critically important in addressing climate change and other associated energy impacts. However, feedback and behavioral interventions face challenges in motivating behavioral change that stem from individual and social psychological factors, as well as broader social and economic problems such as split incentives.

Findings We provide an overview of energy intervention research focusing on (1) different forms of intervention across contexts, (2) combined effects of intervention strategies, (3) consideration of residential demographics and individual characteristics, and (4) additional considerations for successful interventions.

Summary Our review demonstrates that there is significant variation in success across interventions, and that the context, decision structures, and combinatory choices can dramatically affect an intervention. Interventions that combine feedback, motivation, high engagement, and goal setting with well-designed and frequent communication are usually more effective.

Keywords Feedback · Frequency · Incentives · Messaging · Persistence · Pro-environmental behavior · Residential energy efficiency · Self-determination theory · Social comparison

Introduction

In this paper, we focus on information and behavioral efficiency research with specific attention to information feedback, behavioral interventions, and the social psychology of residential efficiency behavior. Over the past decade, an extraordinary revolution has occurred in this area as researchers have intensified their efforts in energy efficiency as an important focal point for addressing climate change. Indeed, many expected that focusing on efficiency broadly would constitute the "easy pickings" of energy use reduction. This has certainly proved true in some areas such as lighting retrofits, infrastructure, and weatherization. Behavioral change has been much more challenging.

Our analysis proceeds as follows. We begin with a general discussion of energy and resource feedback mechanisms, as well as the ways in which feedback programs may be designed. We follow with an overview of recent research in each of three primary areas of feedback design: consumption and data provision, usage education, and motivational approaches. We then proceed to an examination of targeting, engagement, and additional considerations. Our review finishes with a brief overview of some of the most important aspects of feedback intervention in residential energy and resource efficiency. While most of our review focuses on recent scholarship, we include also some older and important research that provides context for our discussion.

Feedback Intervention Overview

The concern for addressing residential energy consumption has an extensive history going back as far as the 1970s and the response to the OPEC energy crisis. This era sparked the emergence of American and global concern for energy conservation and efficiency [1–3]. Research in this area has

This article is part of the Topical Collection on *End-Use Efficiency*

✉ Stephen Bird
sbird@clarkson.edu

[1] Clarkson University, Potsdam, NY, USA

Published online: 17 February 2018

continued, and increased extensively from the late 1990s until the present. Recently, attention has been paid to developing, testing, and clarifying many of the overall trends, approaches, and concepts of this research trajectory.

There is extensive evidence that the obvious economic benefits of implementing conservation behaviors are not enough to motivate behavioral change. There are many reasons for this, including information deficits, lack of education, principal agent problems, or split incentives, in which the person paying for resource use is not the same as the agent using it [4, 5]. Further, the development of improved efficiency technology (improved weatherization, technology, adaptive or smart system technologies) may be too expensive, or suffer from rebound effects, when residents may consume more energy in buildings they know are energy efficient, because they assume that the infrastructural design will compensate for wastefulness [6, 7]. Frederiks et al. provide an overview of the many challenges in behavioral economics that reinforce the gap between action versus knowledge or values [8]. Thus, challenges exist in social, behavioral, and technological realms [9, 10].

Overall Efficacy of Interventions

Overall results of efficiency interventions are enormously mixed, though almost all positive. One recent meta-analysis by Karlin et al. of 42 feedback studies show that feedback is effective overall but with significant variation in effects [11]. They remind us that different feedback types and strategies are inconsistent (correlation coefficient *R*-values vary from − .080 to .480); many different factors affect their success.

By far, the most comprehensive analysis is by Delmas, Fischlein, and Asensio [12••]. They review 156 field trials from 1975 to 2012 and demonstrate an average reduction in energy use of 7.4%. Another one of the earliest and important reviews found that interventions tended to employ "antecedent strategies" (i.e., commitment, goal setting, information, modeling) or "consequence strategies" (i.e., feedback, rewards) [10]. While information provision generated an increase in knowledge but no change in behavior, rewards tended to produce only short-lived effects. Overall, feedback was more impactful to the extent that it was administered frequently.

In 2010, a review of a dozen utility pilot programs in North America showed that in-home displays (IHDs) yielded an average reduction of 7%. Moreover, these savings doubled when customers were also on pre-payment programs [13]. This work also found that time-of-use programs were more effective when used in conjunction with IHDs.

Recent work in Scotland showed reductions of 20% in gas use and 7% in electricity solely via the use of real-time in-color IHDs in apartments and homes [14]. It is rare to see strong results solely from the provision of displays, a point reinforced by others in the critique discussion immediately following [15•]. Screens in this case showed extremely simple, real-time "traffic light" displays that compared current use to the maximum of the most recent day (24 h). These effects were only measured for the first 6 months, so persistence is still a question.

Methodological Concerns

There are a variety of research design concerns and related critiques inherent in feedback and behavioral intervention research that are important to consider. Abrahamse et al.'s initial 2005 review noted many of them which have been further reinforced in recent work [10, 15•, 16, 17]. Much early research relied on self-reports of environmental behavior. Experimental design lacked proper or effective controls, had low participation rates (low *N*), or self-selection problems. Many studies do not address concerns for long-term reductions (aka the concern for persistence or latency).

Study design often has mixed components, which means that it is difficult to determine which factors have led to a reduction. This particular concern is exacerbated by the fact that the use of combinatory or cumulative strategies is more effective for energy reduction. And, many studies do not characterize interventions or concepts in the same way, leading to confusion. Finally, Buchanan et al. note that many energy reduction programs are focusing solely on the use of IHDs or dashboards, without concurrent supportive mechanisms [15•]. The vast majority of literature demonstrates that feedback alone has minimal or null effects as a general rule. However, as we discuss later, when feedback is combined with some other form of behavioral motivation or strategy, the chances of energy savings increase.

How to Think About Energy Intervention Research

Wilson and Dowlatabadi remind us that feedback and behavioral interventions integrate conventional and behavioral economics, technology adoption theory, attitude-based decision making, social and environmental psychology, sociology, public policy, and environmental and energy studies [18]. More recently, Guo et al. provide a relatively comprehensive overview focusing on the underlying logic of the mechanisms that influence feedback by focusing on a broader historical overview of theory addressing resident demographics, social psychological theories, and different intervention mechanisms [19]. Sanguinetti, Dombrovski, and Sikand similarly provide an overview of key eco-design dimensions and reduce the conceptualization of their framework into three dimensions of information, timing, and display which they align with salience, precision, and meaning; all of which inform concerns for attention, motivation, and learning [20].

Our organizational approach synthesizes this previous research in a unique way, in which we attempt to integrate the

various concerns of previous studies. We categorize feedback in three broad conceptual buckets. The first is feedback, the simple provision of energy and resource consumption information and data to the user; this is the "what" dimension. The second is the provision of education on *how* a user can reduce their usage. Finally, feedback can provide information and messages that focus on motivating the user to reduce their usage—in essence, the *why* of energy conservation. Simplistically, it is conceived as *what-how-why*.

We further explore these issues by considering under what context we might target or individuate between different kinds of residents. This is also expanded by engaging with the variety of ways in which intervention design may affect efficacy of a program overall. Finally, we reflect on some critical questions for efficiency intervention in the residential context. These considerations have significant importance for the broader assessment and success of feedback. Our typology of mechanisms, concerns, and contexts that influence residential efficiency interventions is shown in Table 1 below.

Consumption and Usage Information Feedback ("what")

Mechanisms for Success and Meta-analyses

There have been some studies that address how and why feedback effects function in and of themselves to help residents reduce energy consumption. Past research has focused on salience and reminder effects. In essence, feedback can function to increase "the physical and conscious visibility of consumption as well as knowledge about consumption," and to help transform "energy from invisible to visible" [21].

As discussed previously, several studies have conducted meta-analytic evaluations. These help direct the reader to some of the most important strategies for feedback and behavioral intervention. The largest of these, the Delmas meta-analysis, shows that high engagement strategies "providing individualized audits and consulting are comparatively more effective for conservation behavior than strategies that provide historical, peer comparison energy feedback" [12••]. Surprisingly, the meta-analysis shows that for a variety of complicated reasons, external monetary rewards and incentives can increase energy usage (reduce conservation). Finally, this analysis shows that more methodologically rigorous studies show smaller conservation benefits. Other aspects of this paper are discussed in following sections.

Karlin et al. demonstrate that feedback can be construed in terms of *frequency* (how often feedback occurs), *medium* (the ways in which information is delivered), *comparison messages* (either historical or social comparison data), *duration* (the time period that feedback is provided), and *combination* with other interventions such as goal setting or incentives. Interestingly, they find feedback effectiveness is reduced when data become *more* granular. The Karlin study also includes a comprehensive review of the psychological mechanisms that may come into play in energy efficiency interventions.

Guo et al. provide a comprehensive review of factors that have been shown to affect the outcomes of interventions and which can be considered in feedback implementation. They conclude that group size, household inhabitant characteristics (children, age, education, socio-economic status), and building characteristics (size, innate building technological efficiency) are important considerations. They also review psychological factors, including social cognitive theory, behavioral intentions, social norms, and goal development. Other individual differences that may play a role in the success of energy interventions include political orientation [22, 23] and one's level of internalized motivation [16, 17].

There are concerns that interventions for increased conservation may face resistance because of political beliefs or ideology. Tannenbaum et al. [23] show that support for behavioral interventions is stronger when perceived as a program aligned with their political affiliations.

Feedback Needs Support (and the Need for Combinatory/Cumulative Strategies)

A variety of analyses have reinforced the concern that feedback by itself is ineffective without the consideration of additional factors [10]. Comprehensive literature reviews have shown that feedback alone is usually insufficient to generate conservation behavior [24]. Buchanan et al. note the proliferation of different types of feedback devices, particularly IHD smart meter devices. Devices need to improve the contextualization of data, include education, and improve comprehensibility and clarity [15•]. Other studies have shown that solo feedback is ineffective, and that when randomly assigned to an in-home display, no significant improvements in consumption were shown [25].

In another US study, 151 residences were randomly given one of three monitors or IHDs. In this case, some differentiation in device design accounted for a statistically non-significant reduction of 12%, but overall, the effects showed no difference in mean consumption between the equipped and non-equipped residences [26].

Historical Comparison (Past Performance)

Some recent work has shown that choice of different design components can have stronger effects than others. One experiment showed that normative comparison (comparison to group usage) was ineffective unless a historical component was used [27].

An important aspect of the use of historical comparison or past performance is the consideration of anchoring bias. This

Table 1 A typology for thinking about energy use interventions in the residential sphere

Feedback interventions	Targeting and individuation
- Overall efficacy	- Demographic considerations
- Methodological criticisms	- Usage behavior
- Research and disciplinary context	Intervention design considerations
Consumption and usage information ("what")	- Combining strategies
- Mechanisms for success	- Engagement
- Need for combinatory approach	• Gamification
- Historical comparison (past performance)	• Type of personal interactions
Learning and knowledge ("how")	- Message frequency
- Background energy knowledge	- Message medium (type)
- Efficiency action education	- Presentation and design of information
Behavioral motivation ("why")	Additional considerations
- External incentives and penalties	- Persistence/latency
- Social influence/comparison	- Uniqueness of the residential context
• Group versus individual contexts/competition	- Occupancy
• Reciprocity	- High achievers
- Internalized motivation	- Individuation in multi-person residences
• Message framing	
• Goal setting	

is a process of social norms, in which residents are "anchored" or tied to previous data or normed data. McCalley showed that when respondents are told that default temperatures are high, they choose higher temperatures and choose lower temperature settings when they are told that default temperatures are lower [24].

Learning and Knowledge Intervention ("how")

Background Energy Knowledge

An underlying concern for considering the success of an energy efficiency intervention is understanding the background degree of underlying energy knowledge (along with associated degrees of understanding of interactions with environmental concerns, costs, etc.). There is little recent research on this issue, especially in terms of considering the direct relationship of energy knowledge to successful feedback or behavioral interventions, but its importance is strongly emphasized across the literature [12••, 16, 17, 24, 28, 29•]. The best analyses address these concerns via study mechanics such as a comprehensive background energy literacy test [30].

Efficiency Action Education

A critical component in the success of energy efficiency interventions is the concern that even if residents have consumption information and have the motivation to change their behavior, they may not know how to do so. Thus, a critical component of many successfully designed programs is the inclusion of education and feedback on the mechanics or actions needed for successful energy reduction behaviors [12••, 16, 17, 24, 28, 29•].

Recent research has focused on the question of learning versus saliency (frequency). Lynham and colleagues attempt to disentangle the question of learning effects versus saliency effects or reminders [31]. The theoretical hypothesis is that learning processes are even stronger mechanisms for increasing engagement with the process of behavioral change and moderation.

Pasini et al. focus on the different ways in which feedback mechanisms can enhance engagement; however, their work incorporates energy action education in all aspects of feedback design, whether through prompts, dialogues, gamification, or visual representations [32].

Even the most simplistic forms of energy education can have engagement effects. Kang et al. show that distribution of energy education booklets in apartment residences increased pride, overall knowledge, and energy-saving activities [33].

Motivational Intervention

External Incentives and Penalties

Many residential efficiency programs have used incentive programs. These can include bill discounts, pizza parties, or elite use of parking spaces [4, 9, 34]. More rarely, the use of penalties can occur as well. This can include extra charges for high use, penalties in the context of zoning, or other options. Alternately, some have conceived of penalties simply as negative feedback

("you're doing terribly"). Penalties occur rarely because, in the context of household consumption, it can be challenging to assign responsibility to any single inhabitant.

In their experiment, Jain et al. [27] show that penalty mechanisms seem to have no effect, while rewards seem to work best as pecuniary mechanisms (bill discounts, rebates, etc.).

The Delmas meta-analysis shows an unexpected result in which pecuniary feedback and incentives lead to a small increase in energy usage. This can occur because savings may be quite small, or because the pecuniary instinct may crowd out more altruistic intentions, or because the savings accrue to the group and not the individual, a form of free rider problem [12••].

Finally, another recent study examined the combined effects of conservation messaging with cost-based framing and discussion had little initial effect and no effect after 2 weeks. Alternately, the same approach in which conservation was combined with health framed messaging had a robust 8–10% reduction over a 100-day period [35]. These results suggest that more personal and substantive motivators are more effective than monetary ones (we return to this idea in the "Internalized Motivation" section below).

Social Influence/Comparison

As discussed earlier, an enormous amount of work in the field has focused on the arena of social influence and comparison. There is a variety of ways in which behavior is affected by what other people do or think. One recent meta-analysis reviews 29 studies to determine the overall effect of social influence mechanisms. Results showed strong effects overall, and, compared to other forms of intervention, somewhat smaller positive effects [29•].

Another recent study showed the effect of public praise and shaming by identifying single- and double-occupant room numbers (names were not disclosed but presumably friends and acquaintances would know identities) as above average (less use) or below average (more use) energy consumers [36]. This constitutes one of the few studies in which the use of publicized information for (presumable) shaming has occurred. It is not clear to what degree such an approach could be generalized to a broader population for privacy reasons (this was done in university dorms with a partial subset of participants). The availability of dashboard energy feedback information alone produced no effects compared to controls whereas the use of publicity and feedback information resulted in a 20% reduction in use.

Other researchers have implemented feedback in socially contextualized ways which has resulted in less consumption [37]. In this context, students were allowed to review a peer's consumption information against their own (if they had both identified each other as belonging to a friends and acquaintances social network). Again, this was a student context and it is not clear how generalizable this form of approach might be. Effects were small in this case, but the research was limited by a small sample size.

Other researchers developed "normative" feedback messages on energy consumption in dormitories and found that students with a high concern for social norms had a 14% reduction in energy use, but students with less concern had a 5% reduction. Duration of the effect was also higher for those with high concern for social norms [38].

Group Versus Individual Contexts/Competition and Community

Another strand of research addresses the interplay between individuals and larger group norms, often in a competitive context. Group feedback is effective because it makes it obvious that others are actively engaged in energy conservation. It also becomes clear that an individual can make an important contribution to energy conservation and help reduce energy-related problems [39].

One of the more well-known studies assesses the use of *OPower's* program of utility comparison of a resident to the average use of local neighbors [40]. The OPower program is unique in its ability to achieve a deep and meaningful differential at scale even if the effect itself is small (2%). What is particularly interesting is that the highest consumption households achieve the highest reductions (> 6%).

Group size in the residential context can be an important factor for the social influence effect. Energy consumption can increase in group-level situations that involve more people because it can be harder to identify higher-consumption users, can allow for free-riding, and reduce interpersonal trust and collectivist values [41]. Incidentally, this research also substantiated past concerns for self-reports and past concerns for the accuracy of self-reported energy use. Residents had self-reported energy use that was substantially less than the group per capita average.

Researchers have also addressed the role of the community effect. In creating a community-level program designed to reinforce positive perceptions and community cohesion around an energy conservation program, researchers found that residents had higher levels of engagement, and longer-term engagement than control areas without such a program. Engagement amongst women was significantly higher in this particular implementation [42]. There appears to be real value in engaging with communities as broadly as possible in energy conservation programs.

Alternately, large-scale public graphic displays of building real-time energy use (without additional components or strategies of engagement or education) were found not to improve behavioral energy use decisions [43]. The implementation helped save energy only because building managers could detect large-scale fault problems and address them. Another strand of literature occurs in commercial buildings (of which

some are large-scale residential condo or public housing buildings) that use public displays which integrate historical benchmarking [44]. Benchmarking compares current usage patterns to the historical benchmark, and has in some cases been aligned to longer-term reductions in energy use, but it is not at all clear that feedback and behavioral change are responsible for the improvements. It is more likely that facility management responses are the cause.

Reciprocity

One of the mechanisms in social influence processes includes concerns for equity and reciprocity. Recent immersive experimental tests show that participants are much more willing to make energy reduction actions if they perceive another person is similarly sacrificing or helping in the action [45]. Quite interestingly, the researchers saw carryover effects from the virtual experiment in terms of actual behavior in the physical environment after the experiment was over, suggesting that participants had been primed in their experience. As in many experiments, a significantly greater participation rate would increase confidence in these results.

Internalized Motivation

Harnessing individuals' pro-environmental behavior (or PEB) is challenging because the motivational dilemma underlying pro-ecological action is complex, spanning public, personal, and social domains [46, 47]. Further, engaging in sustainable behavior is not inherently rewarding or egoistic. Instead, it involves trade-offs amongst personal comfort, economic concerns, and social/global welfare that may not have immediate or personal benefits [48]. Incentives, punishments, financial savings, rewards, rules, social norms, and competitions are all forms of external constraints—which tend to use pressure to influence behavior without changing personal motivation [49]. This can also lead to persistence problems if external controls are removed. In many situations (principal agent, commons, split incentives), it can be hard to implement external controls. As a result, research has emerged that focuses on developing internalized or personal motivation for conservation behavior.

In recent work, Sweeney et al. [50] found that more personal motivation predicted more self-reported energy conservation. In this experiment, participants participated in an energy-saving program, and those exposed to a program designed to increase motivation for pro-environmental behaviors had a significant but small decrease in energy usage.

Evidence suggests that when people experience a sense of autonomy and personal motivation while engaging in PEB, they are more likely to sustain it [51, 52]. Recent work resulted in 20% reductions in electricity use when participants were part of a feedback program that combined specific action-focused energy goals based on their own self-developed motivations in a workshop [16, 17]. The intervention provided informative rationales for resource conservation (e.g., climate change, energy security, resource depletion, public health) and then asked participants to identify their own reasons for saving water and electricity.

Message Framing

An additional concern for triggering appropriate concerns and motivations is the question about how information is conceived and framed. For instance, recent work (discussed earlier as well) combined conservation messages with either a cost-saving or health-oriented frame. A health frame (along with conservation) produced persistent 8–10% reductions while cost concerns and conservation had minimal effects that attenuated quickly [35].

Other recent work framed water consumption in terms of energy use (associated embodied energy) as opposed to just pure "gallons"-level feedback. The energy frame for water use created a small but statistically robust reduction in water use [53].

Goal Setting

Quite simply, goal progress requires feedback and feedback requires a goal; the effectiveness of energy feedback appears to critically depend on whether the user has a *specific energy goal* [10, 28, 54]. Feedback services are futile when energy users lack conservation goals that give feedback information context and focus. It was also noticed that if a difficult goal was combined with feedback, it was more effective in reducing energy use compared to a relatively easy goal combined with feedback [55]. In lab experiments, McCalley shows that goal setting is an important component of feedback success as a combined effect. In particular, the use of goals as an attention focusing device for engagement is shown [24]. Recent meta-analysis by Karlin et al. reinforces the importance of goal setting in combination with feedback as a mechanism for improved success [11].

Targeting and Individuation

Demographic Considerations

A variety of considerations can be considered when implementing residential energy efficiency programs. For instance, recent research customized feedback to low-income groups. This included the feedback of specific and customized consumption information, education focused on the social aspects and typology of the dwelling, and response to surveyed habits [56].

Khashe et al.'s experimental research similarly found significant effects between personality traits and message compliance [45]. Other research has focused on the political ideology and its relationship to internalized motivation and pro-environmental behavior [22]. A large literature exists on the relationship between ideology and environmental beliefs and behavior, but little has been done to address this knowledge in the context of energy efficiency programs.

As discussed early, Guo et al. remind us that group size, household inhabitant characteristics (children, age, education, socio-economic status), and building characteristics (size, innate building technological efficiency) are important considerations and have been shown to have important ramification for successful efficiency interventions [19].

Usage Behavior (Targeting Depending on Energy Use Type)

Other research targets residents by consumption, or other differences in energy behavior. Some researchers have characterized residents into differentiated usage groups (low, medium, high) and noted the differential responses by those groups, and their participation or engagement with different activities [57]. Recent work using smartphone apps with people in different thermal and heating contexts had higher effects on higher temperature setting residents [58]. Much more work is required to address targeted eco-feedback based on consumption patterns.

Intervention Design Considerations

Combinatory and Cumulative Strategies

Research has shown that the combination of tailored information, goal setting, and feedback has been successful in reducing household energy consumption. Interventions work better when used in conjunction, because different households are prevented from action by different barriers [39]. This is particularly true for combined interventions that include feedback and goal setting, since feedback is more effective when there is a benchmark from which to compare it [10, 16, 35].

A recent study demonstrates that residents who have multiple goals (fun, saving energy, reducing costs, reducing inconvenience) for their energy behavior are more likely to use energy feedback systems or smart meters [59]. This research is important because it also shows that multiple goals improve persistence of engagement. The same study also shows that differentiating goal "types" is both possible and provides cumulative predictive power for energy feedback engagement.

Ramos et al. demonstrate that information programs (energy certificates, feedback, energy audits) have mixed effects in solo, but are much more effective in combination, with each other, and with other strategic program components such as goal setting [60].

Other research focuses on combining smart meters with dashboard or paper feedback that increases interpretational information and action education tips, as compared to smart meters alone. Not only is reduction increased, but persistence of behavior change is increased with a 5% electricity consumption reduction over an 11-month period [61].

Chen et al. [62•] found that feedback engagement was increased by the use of email reminders. Even then, only 50% of users engaged with their website dashboard. Alternately, the use of dashboard screens on the wall within residences seems to have higher engagement (focus group feedback) but more evidence is needed [16, 17, 62•].

Engagement

A wide variety of strategies and concerns must be considered to improve engagement with energy conservation programs and behavior change. Engagement, or more simply, participation, is the critical linchpin for any successful energy intervention, especially long term.

Gamification

One of the more important ideas to emerge in the last decade or so is the gamification of energy feedback. In these situations, a variety of design and feedback strategies can be implemented that make the process of engaging with energy programs, and actually implementing changed behavior fun, engaging, and fulfilling. The most obvious emergent forms were the development of dormitory competitions in the late 1990s in which different floors or different dorms competed against each other for reputational gains, or to win tangible benefits such as pizza parties [63–66]. The literature on this approach is voluminous; however, there are significant concerns for persistence in this tactic, with little literature that demonstrates it can continue past the end of a program, and concerns also that game strategies are not methodologically rigorous.

Type and Degree of Personal Interactions

Unsurprisingly, personal interaction is a strong predictor of energy reduction results in efficiency programs. This is most potently noted in the Delmas meta-analysis which shows that personalized consultations and audits result in a strong degree of response [12••]. This is despite the fact that Ramos et al. have concerns for reduced effectiveness in audit processes for feedback [60]. The Smart Housing Project described earlier used workshop experiences as "priming" for student engagement which then reverted to messaging [16]. Overall, extensive evidence exists across several of the reviews that situations that

include high-intensity personal interactions are likely to increase engagement and energy savings.

Message Frequency and Differentiation

A variety of researchers have focused on the success and importance of message frequency [10, 29•]. Indeed, reminders are an important part of feedback and it is critical to increase attention to and awareness of energy behavior—especially since the impact of energy behaviors is often invisible.

A second concern is the degree to which messages differentiate, so their content is less predictable and more engaging [16, 17]. Little research exists that specifically addresses the use of differentiated messages as a way to increase engagement, and thus program success. This is likely a rich arena for future research.

Message Medium (Type)

The concern for the way in which messages are provided to participants or residents can potentially be an important concern. This can include mediums of message, email, text, public provision, unit provision, social media post, personal or group dashboard, lights, screen, etc. We separate this concern from the specific concern for dashboard design, human factors research, and determination of which information is most useful to present (which we address just below). Again, the concern for message medium is understudied and provides an opportunity for future research.

One particularly emergent area is the potential use of smartphone apps (applications). Vellei et al. successfully use an app as a real-time mechanism for local temperature in a building, and response messaging to reinforce the use of appropriate clothing levels. This allowed the implementation of slightly lower radiator and room temperatures without making residents uncomfortable [58].

Presentation and Design of Information

An enormous amount of work is just emerging in the area of information and feedback design and presentation. It is clear that device design itself can have real effects. In one utility implementation, only one kind of smart meter monitor was effective in reducing mean consumption (by 12%) in homes as compared to two variants of another which had no effect [26]. Device design can have significant effects.

For instance, researchers compared the provision of electricity kilowatt consumption, consumption and cost, and consumption and social normative frames [67]. The combination of consumption information combined with normative context resulted in 9% reductions in the short-term (1 week) and 7% reductions over a 3-month period. Interestingly, this intervention also included the provision of educational materials in each context, and alone. Again, the educational material only seemed to have an effect in the context of the social norm message.

Other researchers have developed conceptual frameworks that help organize and characterize various behavioral mechanisms in the presentation of information. They classify information into three types: attention, learning, and motivation. They show different relationships to these concepts in terms of three types of dimensions. "Information dimensions include granularity, metrics, valence, and contextual information. Timing dimensions include latency, strategic timing, and frequency and duration. Display dimensions include medium, modality, style, location, audience, and response requirement" [20].

Other concerns have focused on the beneficial uses of color and the need for simple, easily conceptualized information display [14], different forms of visualization, and IT concerns for integration or portability [68]. Others doing experimental work have shown that residents prefer granular information and monetary equivalents are actually not as useful as aggregated kilowatt hour feedback [69]. Simplified information is more effective, even if less personalized. More research is needed to tease out the reasons for this.

Additional Considerations

Persistence/Latency

The concern for how long an energy intervention lasts is a critically important concern. If university students exposed to residential efficiency programs continue their learned behaviors throughout the rest of their life, it will significantly affect their energy costs, and provide extensive social benefits as well. As discussed in the "Introduction" section, the concern for persistence outcomes, especially past the 12-month mark, is an area that has not been addressed nearly enough.

Hargreaves et al. [70] report that in a field trial of real-time displays, the monitors gradually became "'backgrounded' within normal household routines and practices." Monitors helped increase knowledge and confidence in energy use, but also contributed to a concern that reductions were minor, had limits, and were not supported by broader social, policy, and market initiatives.

Social norm effects do seem to reinforce persistent changes in behavior. In one set of experiments, 14% reductions were achieved only over slightly longer periods of time, and only amongst those with higher levels of concern for social norms [38]. This research was somewhat encouraging because it showed that increasing the duration of the provision of messages increased persistence of behavior change.

Similarly, the Schleich study showed that the addition of supplementary materials (dashboard or paper feedback that increases interpretational information and action education

tips) to feedback meters created a persistent (11 month) additional reduction of 5% in energy usage [61].

Uniqueness of the Residential Context

Several studies remind us that the residential context is unique in terms of building energy efficiency. As a result, we should expect the development of energy efficiency programs in different kinds of building environments to function differently. Further, it is possible that the residential context, in which values and other personality components play a big role, that addressing efficiency could be a more difficult problem. A recent work for energy saving in the workplace context achieved almost 19% reductions in energy use, simply by targeting three behavioral change interventions [71]. In this work, there was little significant change to pro-environmental attitudes or norms. A similar kind of change in the residential context, for many of the reasons discussed earlier in the paper, could be hard to achieve.

Occupancy

One of the more challenging questions in residential contexts is determining the effect of occupancy, especially in units with three or more residents. Obviously, some reactive "smart" technology (lighting movement monitors, smart thermostats) can function to address this concern, but it is more difficult if residents have varying and inconsistent schedules, and especially if they travel.

Some recent work has focused on the development of occupancy patterns as a part of the feedback process, as part of a customization of energy use information [72]. This work shows that personalized occupancy feedback can help improve behavioral change in certain circumstances and help maximize opportunities for energy use reduction.

High Achievers

A second challenge in residential energy efficiency is to determine how to identify and treat already high-performing (i.e., low use) residents or participants. Studies discussed earlier include discussions of targeting high-use consumers differently than the average [57, 58]. However, what is not clear is how to address users that start at the lowest levels of energy consumption, or users that have achieved those low levels. Giving additional messages or behavioral change prompts to someone who is using very little energy will not provide additional benefits. Little research exists that addresses this concern.

Individuation in Multi-Person Residences

Finally, as we have discussed at several points, a variety of researchers have discussed the importance of targeting and engaging with the individual motivations, values, and characteristics of energy users. The challenge here is that users often live together and may be dramatically different from one another. Some obvious stereotypical examples might include a high energy use "gamer" and an ecologically minded outdoor enthusiast in a college dorm, or a stingy parent who is never cold and their constantly freezing teenager. In such situations, the challenge of addressing concerns for targeting specific residents while the fact that energy decisions are sometimes made at group levels (house temperature) or individual levels (shower length and hot water use) is complicating factor that deserves more attention in future interventions.

Conclusion

The multi-disciplinary field of research on feedback and behavioral interventions in residential energy consumption is rich, almost overwhelming, in its components and activities. This is exemplified by the sheer number of studies in Delmas et al.'s meta-analysis [12••]. There have been excellent advances in our understandings of some of the most powerful effects in the field, particularly in terms of social norms, internalized motivation, and the importance of engagement and combined approaches.

Similarly, new advances in information communication styles, types, and strategies demonstrate significant improvements over past interventions. However, new research is needed to address concerns for persistence, occupancy, and the individuation problem. We also need ways in which to address concerns for "high achiever" residents.

We reiterate in particular the concern by Buchanan et al. [15•] for a deeper level of rigor and consistency in the field; particularly in designing and implementing thoughtful, clear, and replicable studies and interventions. There remains much to do; work in this area can help solve critically important global concerns for climate change and energy use in a sector that has many challenges in implementation.

Acknowledgements We appreciate the research assistance of Amanda Sherman for parts of this paper.

Funding Information This work was supported in part by the New York State Energy Research and Development Authority (NYSERDA), under contract no. 32013.

Compliance With Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Seligman C, Darley JM, Becker LJ. Behavioral approaches to residential energy conservation. Energ Buildings. 1978;1:325–37.
2. Becker LJ. Joint effect of feedback and goal setting on performance: a field study of residential energy conservation. J Appl Psychol. 1978;63:428–33.
3. Dixon RK, McGowan E, Onysko G, Scheer RM. US energy conservation and efficiency policies: challenges and opportunities. Energy Policy. 2010;38:6398–408.
4. Bird S, Hernández D. Policy options for the split incentive: increasing energy efficiency for low-income renters. Energy Policy. 2012;48:506–14.
5. Gillingham K, Harding M, Rapson D. Split incentives in residential energy consumption. Energy J. 2012;33
6. Frondel M, Vance C. Energy efficiency: don't belittle the rebound effect. Nature. 2013; https://doi.org/10.1038/494430c.
7. Gillingham K, Rapson D, Wagner G. The rebound effect and energy efficiency policy. Rev Environ Econ Policy. 2016;10:68–88.
8. Frederiks ER, Stenner K, Hobman EV. Household energy use: applying behavioural economics to understand consumer decision-making and behaviour. Renew Sust Energ Rev. 2015;41:1385–94.
9. Granade HC, Creyts J, Derkach A, Farese P, Nyquist S, Ostrowski K (2009) Unlocking energy efficiency in the U.S. economy. Mckinsey & Company
10. Abrahamse W, Steg L, Vlek C, Rothengatter T. A review of intervention studies aimed at household energy conservation. J Environ Psychol. 2005;25:273–91.
11. Karlin B, Zinger JF, Ford R. The effects of feedback on energy conservation: a meta-analysis. Psychol Bull. 2015;141:1205–27.
12.•• Delmas MA, Fischlein M, Asensio OI. Information strategies and energy conservation behavior: a meta-analysis of experimental studies from 1975 to 2012. Energy Policy. 2013;61:729–39. **Excellent meta-analysis of many factors with a comprehensive overview of all experimental studies.**
13. Faruqui A, Sergici S, Sharif A. The impact of informational feedback on energy consumption—s survey of the experimental evidence. Energy. 2010;35:1598–608.
14. Stinson J, Willis A, Williamson JB, Currie J, Smith RS. Visualising energy use for smart homes and informed users. Energy Procedia. 2015;78:579–84.
15.• Buchanan K, Russo R, Anderson B. The question of energy reduction: the problem(s) with feedback. Energy Policy. 2015;77:89–96. **Provides a comprehensive critique of many of the challenges inherent in the development of feedback and behavioral motivation.**
16. Legault L, Bird S, Powers SE, Sherman AK, Schay A, Hou D, Janoyan K (2018) Impact of a motivational intervention and interactive feedback on electricity and water consumption: a smart housing field experiment. Under Review
17. Bird S, Hou D, Janoyan K, Legault L, Powers SE, Fox L, Rowe A, Schay A, Sherman AK (2016) Clean energy and smart student housing: motivational interventions for improved energy efficiency in university housing. New York State Energy Research and Development Authority, Albany, NY
18. Wilson C, Dowlatabadi H. Models of decision making and residential energy use. Annu Rev Environ Resour. 2007;32:169–203.
19. Guo Z, Zhou K, Zhang C, Lu X, Chen W, Yang S. Residential electricity consumption behavior: influencing factors, related theories and intervention strategies. Renew Sust Energ Rev. 2018;81:399–412.
20. Sanguinetti A, Dombrovski K, Sikand S. Information, timing, and display: a design-behavior framework for improving the effectiveness of eco-feedback. Energy Res Soc Sci. 2018;39:55–68.
21. Buchanan K, Russo R, Anderson B. Feeding back about eco-feedback: how do consumers use and respond to energy monitors? Energy Policy. 2014;73:138–46.
22. Sherman AK, Rowe AJ, Bird S, Powers S, Legault L. Motivational orientation explains the link between political ideology and proenvironmental behavior. Ecopsychology. 2016;8:239–49.
23. Tannenbaum D, Fox CR, Rogers T. On the Misplaced Politics of Behavioural Policy Interventions. Nature Human Behaviour. 2017;1(7):0130. https://doi.org/10.1038/s41562-017-0130.
24. McCalley LT. From motivation and cognition theories to everyday applications and back again: the case of product-integrated information and feedback. Energy Policy. 2006;34:129–37.
25. Nilsson A, Bergstad CJ, Thuvander L, Andersson D, Andersson K, Meiling P. Effects of continuous feedback on households' electricity consumption: potentials and barriers. Appl Energy. 2014;122:17–23.
26. Alahmad MA, Wheeler PG, Schwer A, Eiden J, Brumbaugh A. A comparative study of three feedback devices for residential real-time energy monitoring. IEEE Trans Ind Electron. 2012;59:2002–13.
27. Jain RK, Taylor JE, Peschiera G. Assessing eco-feedback interface usage and design to drive energy efficiency in buildings. Energ Buildings. 2012;48:8–17.
28. Fischer C. Feedback on household electricity consumption: a tool for saving energy? Energ Effic. 2008;1:79–104.
29.• Abrahamse W, Steg L. Social influence approaches to encourage resource conservation: a meta-analysis. Glob Environ Chang. 2013;23:1773–85. **This meta-analysis is not as comprehensive as Delmas, but provides an effective and more detailed discussion and analysis of motivation and social psychology factors in behavioral change.**
30. DeWaters J, Powers S. Establishing measurement criteria for an energy literacy questionnaire. J Environ Educ. 2013;44:38–55.
31. Lynham J, Nitta K, Saijo T, Tarui N. Why does real-time information reduce energy consumption? Energy Econ. 2016;54:173–81.
32. Pasini D, Reda F, Häkkinen T. User engaging practices for energy saving in buildings: critical review and new enhanced procedure. Energ Buildings. 2017;148:74–88.
33. Kang NN, Cho SH, Kim JT. The energy-saving effects of apartment residents' awareness and behavior. Energ Buildings. 2012;46:112–22.
34. Geller H, Harrington P, Rosenfeld AH, Tanishima S, Unander F (2006) The experience with energy efficiency policies and programmes in IEA countries: learning from the Critics. Energy Policy 34:556–573
35. Asensio OI, Delmas MA. The dynamics of behavior change: evidence from energy conservation. J Econ Behav Organ. 2016;126:196–212.
36. Delmas MA, Lessem N. Saving power to conserve your reputation? The effectiveness of private versus public information. J Environ Econ Manag. 2014;67:353–70.
37. Jain RK, Gulbinas R, Taylor JE, Culligan PJ. Can social influence drive energy savings? Detecting the impact of social influence on the energy consumption behavior of networked users exposed to normative eco-feedback. Energ Buildings. 2013;66:119–27.
38. Anderson K, Song K, Lee S, Krupka E, Lee H, Park M. Longitudinal analysis of normative energy use feedback on dormitory occupants. Appl Energy. 2017;189:623–39.
39. Abrahamse W, Steg L, Vlek C, Rothengatter T. The effect of tailored information, goal setting, and tailored feedback on household

energy use, energy-related behaviors, and behavioral antecedents. J Environ Psychol. 2007;27:265–76.
40. Allcott H. Social norms and energy conservation. J Public Econ. 2011;95:1082–95.
41. Carmi N, Mostovoy N. The effect of group size on energy consumption by communal electricity users. J Environ Psychol. 2017;54:50–6.
42. Burchell K, Rettie R, Roberts TC. Householder engagement with energy consumption feedback: the role of community action and communications. Energy Policy. 2016;88:178–86.
43. Timm SN, Deal BM. Effective or ephemeral? The role of energy information dashboards in changing occupant energy behaviors. Energy Res Soc Sci. 2016;19:11–20.
44. Chung W. Review of building energy-use performance benchmarking methodologies. Appl Energy. 2011;88:1470–9.
45. Khashe S, Heydarian A, Becerik-Gerber B, Wood W. Exploring the effectiveness of social messages on promoting energy conservation behavior in buildings. Build Environ. 2016;102:83–94.
46. Kollmuss A, Agyeman J. Mind the gap: why do people act environmentally and what are the barriers to pro-environmental behavior? Environ Educ Res. 2002;8:239–60.
47. Larson LR, Stedman RC, Cooper CB, Decker DJ. Understanding the multi-dimensional structure of pro-environmental behavior. J Environ Psychol. 2015;43:112–24.
48. Pelletier LG, Baxter D, Huta V. Personal autonomy and environmental sustainability. In: Human autonomy in cross-cultural context. Dordrecht: Springer; 2011. p. 257–77.
49. Lavergne KJ, Sharp EC, Pelletier LG, Holtby A. The role of perceived government style in the facilitation of self-determined and non self-determined motivation for pro-environmental behavior. J Environ Psychol. 2010;30:169–77.
50. Sweeney JC, Webb D, Mazzarol T, Soutar GN. Self-determination theory and word of mouth about energy-saving behaviors: an online experiment. Psychol Mark. 2014;31:698–716.
51. Cooke AN, Fielding KS, Louis WR. Environmentally active people: the role of autonomy, relatedness, competence and self-determined motivation. Environ Educ Res. 2016;22:631–57.
52. Deci EL, Ryan RM. Self-determination theory: a macrotheory of human motivation, development, and health. Can Psychol. 2008;49:182.
53. Jeong SH, Gulbinas R, Jain RK, Taylor JE. The impact of combined water and energy consumption eco-feedback on conservation. Energ Buildings. 2014;80:114–9.
54. Locke EA, Latham GP (2015) Breaking the rules: a historical overview of goal-setting theory. In: Elliot AJ (ed) Advances in motivation science. Elsevier, pp 99–126
55. Abrahamse W, Steg L, Vlek C, Talib R. The Effect of Tailored Information, Goal Setting, and Tailored Feedback on Household Energy Use, Energy-Related Behaviors, and Behavioral Antecedents. Journal of Environmental Psychology. 2007;27(4): 265–76.
56. Podgornik A, Sucic B, Blazic B. Effects of customized consumption feedback on energy efficient behaviour in low-income households. J Clean Prod. 2016;130:25–34.
57. Khosrowpour A, Xie Y, Taylor JE, Hong Y. One size does not fit all: establishing the need for targeted eco-feedback. Appl Energy. 2016;184:523–30.
58. Vellei M, Natarajan S, Biri B, Padget J, Walker I. The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation. Energ Buildings. 2016;123:179–91.
59. Gölz S, Hahnel UJJ. What motivates people to use energy feedback systems? A multiple goal approach to predict long-term usage behaviour in daily life. Energy Res Soc Sci. 2016;21:155–66.
60. Ramos A, Gago A, Labandeira X, Linares P. The role of information for energy efficiency in the residential sector. Energy Econ. 2015;52:S17–29.
61. Schleich J, Faure C, Klobasa M. Persistence of the effects of providing feedback alongside smart metering devices on household electricity demand. Energy Policy. 2017;107:225–33.
62.• Chen VL, Delmas MA, Kaiser WJ. "Real-Time, Appliance-Level Electricity Use Feedback System: How to Engage Users?" Energy and Buildings 2014;70:455–62. https://doi.org/10.1016/j.enbuild.2013.11.069. **A cutting edge implementation of feedback, messaging, and public information.**
63. Grossberg F, Wolfson M, Mazur-Stommen S, Farley K, Nadel S (2015) Gamified energy efficiency programs. American Council for an Energy-Efficient Economy, Washington, DC
64. Sintov N, Dux E, Tran A, Orosz M. What goes on behind closed doors? How college dormitory residents change to save energy during a competition-based energy reduction intervention. Int J Sustain High Educ. 2016;17:451–70.
65. Sintov ND, Desario G, Prescott C (2010) Effectiveness of a competition-based intervention in promoting pro-environmental behavior in a university residential setting. In: ACEEE Summer Study on Energy Efficiency in Buildings. pp 322–336
66. Edward V, Jones CM (2015) A review of energy reduction competitions: what have we learned?
67. Schultz PW, Estrada M, Schmitt J, Sokoloski R, Silva-Send N. Using in-home displays to provide smart meter feedback about household electricity consumption: a randomized control trial comparing kilowatts, cost, and social norms. Energy. 2015;90:351–8.
68. Murugesan LK, Hoda R, Salcic Z. Design criteria for visualization of energy consumption: a systematic literature review. Sustain Cities Soc. 2015;18:1–12.
69. Krishnamurti T, Davis AL, Wong-Parodi G, Wang J, Canfield C. Creating an in-home display: experimental evidence and guidelines for design. Appl Energy. 2013;108:448–58.
70. Hargreaves T, Nye M, Burgess J. Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. Energy Policy. 2013;52:126–34.
71. Mulville M, Jones K, Huebner G, Powell-Greig J. Energy-saving occupant behaviours in offices: change strategies. Build Res Inf. 2017;45:861–74.
72. Coleman MJ, Irvine KN, Lemon M, Shao L. Promoting behaviour change through personalized energy feedback in offices. Build Res Inf. 2013;41:637–51.