Effective design of in-home energy efficiency displays: a proposed architecture based on empirical evidence

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Abstract

Demand-side management is widely considered a key tool to achieve the decarbonization on the energy sector. In this regard, providing end users with detailed information about their consumption patterns is key in order to enable them to make informed decisions to reduce or adapt their energy consumption. This requires the deployment of feedback interactive technologies such as in-home displays, dedicated apps/web portals, or ambient interfaces. There have been extensive research and numerous pilot experiences on the effect of these technologies on end-user behavior, which identified the importance of an appropriate device design to achieve the desired demand response. However, a clear framework to design these feedback technologies in order to ensure the desired behavioral change does not exist.

In order to fill this gap, this paper presents an exhaustive review of existing research on feedback, focusing especially on interactive devices. This review has resulted in the identification of ten key parameters that should be taken into account by device designers, including the type and form of the information provided (medium, units, disaggregation level, comparisons, goal setting), design of the interface and devices themselves, the possible inclusion of penalties and rewards, and privacy concerns. Recommendations to implement them in such a way that end-user interaction and response is maximized are provided. These recommendations would jointly make in-home displays more effective in creating the desired household behavioral change to maximize energy conservation. Moreover, critical areas where further research is necessary before a sound recommendation can be made are identified.

Keywords: energy efficiency, demand response, eco-feedback, in-home display, end-user behavior

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1. Introduction

Achieving the emissions goals set in the Paris Agreement demands a societal effort. Households' energy consumption is one of the targets of governmental policies, as energy consumption in the use phase causes the largest environmental impacts [1]. Households are encouraged, inter alia, to reduce energy consumption by achieving efficiency gains or reducing environmental impact [2], by conservation [3, 4], or by load-shifting [5] to times where energy sources are cleaner. Demand-Side Management (DSM), which comprises both demand response (DR) and energy conservation, is a widely used term to describe programs developed to influence the energy usage patterns of customers [6, 7].

These programs are oftentimes implemented in practice by means of eco-feedback devices that provide users with information about their household energy consumption. Feedback can be provided by different means: indirectly via billing or web portals, or directly, by using display devices [8]. In turn, display devices comprise interactive devices such as (1) mobile apps or websites, (2) in-home displays providing graphic and textual visualizations [9] and (3) ambient interfaces. More complex tools not only provide feedback but also allow users to manage their energy consumption by switching on and off appliances or heating systems.

These devices facilitate two-way communication between power utilities, energy suppliers and/or energy service companies (ESCOs), and home consumers [10, 11]. Whereas interactive displays provide consumers with abundant and accessible information so that they can learn about their energy spending habits and change them, ambient displays rely on "pre-attentive" processing of information [12]. The main difference with the interactive displays is that ambient interfaces do not give specific information about energy expenditures in the form of text or numbers, but simply alert the household that their electricity expenditure has changed or is about to change [13, 14]. The main focus of analysis in this paper is interactive devices, and more specifically, in-home displays as most research has examined this type of device; yet, it also addresses the existing research on ambient energy artefacts.

The introduction of in-home displays has been boosted by a desire to empower energy consumers, and by the development of feedback technologies as a mean to gain consumer engagement in energy conservation [10, 15, 16]. In-home displays are advocated as they provide users with real-time information about energy spending, facilitating a better understanding of how their daily practices affect energy consumption [9]; they increase awareness of energy saving alternatives; and they provide incentives to reduce consumption [17]. In a nutshell, they are deemed effective as they make households more aware of energy consumption and more knowledgeable about what causes this consumption. This eventually gives users control over their energy consumption, which will ultimately result in energy savings.

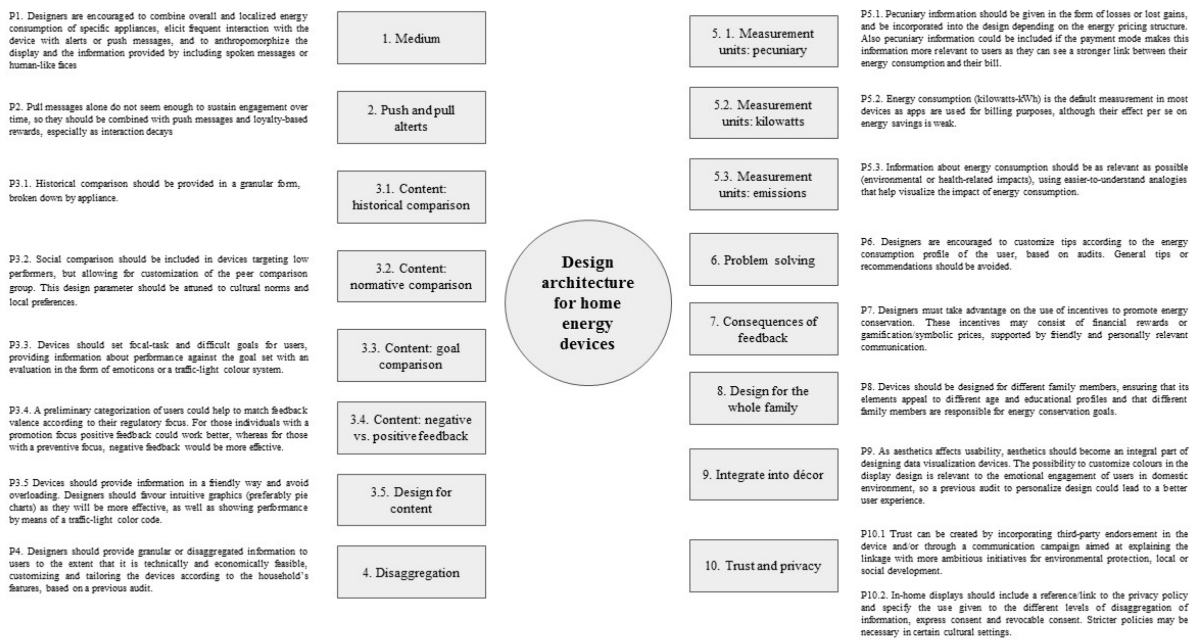
Yet, past studies have found wide differences in the amount of energy savings actually achieved following feedback-related interventions [5, 9, 18, 19]. These differences have been attributed to different factors, such as the characteristics of the device, the characteristics of the household (notably, their motivation and their actual possibilities of reducing their energy consumption) or to the context (i.e. climatology constraints) [20-24]. The latter two factors are difficult or

impossible to control; thus, the most plausible way of increasing energy savings in eco-feedback-based interventions is by improving the design of the device.
The negative consequences of inadequate device design have been previously emphasized as a major constraint for the scope of eco-feedback potential [25, 26]. However, we lack a framework that allows designers to maximize the potential of interactive devices to ensure the desired households' behavioral change. This paper aims to provide such framework.
An exhaustive review of approximately 90 studies on eco-feedback interventions, design of feedback devices and ambient energy artefacts obtained from Google Scholar and WOS (using the keywords "eco feedback" OR "feedback AND energy" OR "feedback AND shift load" OR "smart meter" AND feedback OR "energy display" AND household) was conducted, supplemented with meta-analyses on energy savings and energy conservation. This review was complemented with ad hoc searches to find insights to complement those relevant aspects for which scant research was found.
Consistent with the objective of the study, papers were analyzed to identify key parameters of design that may affect outcomes. Work on gamification was excluded from the analysis and readers are referred to a review recently published in the journal for more information [27].
More specifically, ten parameters of design are identified and courses of action are recommended for each of them. Based on available evidence, these ten design parameters would jointly make in-home displays more effective in creating the desired household behavioral change to maximize energy conservation. This paper contributes to existing literature by providing a guide to device designers based on sound empirical evidence. It also identifies critical areas for further research.

2. Parameters to consider for an effective design of in-home displays and eco-feedback devices

Then design dimensions for interactive devices that are deemed key for the effectiveness of energy efficiency programs. This section describes these ten parameters in detail and provide a set of recommendations to enhance energy conservation strategies using in-home displays.
It is important to note that these dimensions are not completely orthogonal and they may overlap with one another. Overall, these dimensions can be considered to compose the architectural design for interactive devices, or, in other words, they provide an empirically grounded framework for designers in order to maximize households' energy conservation. Figure 1 presents an overview of this architectural design, including the proposals (P1 to P10) for each one of the aforementioned ten parameters (in some case broken down into several sub-topics).

Figure 1. Architectural design of interactive devices for eco-feedback



2.1. Medium of communication with end users

Interactive devices have proven more effective in driving energy savings than written feedback via emails or bills for three reasons: they provide real-time [5, 20, 28-32] or, at least, more frequent energy consumption data than billings or emails they can be attuned to users' profile, and they can flexibly accommodate different behavioral interventions, as discussed later [33]. Yet, real-time feedback per se does not consistently lead to reduced energy use [28, 34]. The number of interactions with the device can explain these differences in results. Even if the device provides real-time feedback, if users do not engage with it, the potential energy savings are jeopardized. Thus, interactive displays demand involvement from users. There is some evidence that interaction with the device predict energy savings [9, 23, 36]. Thus, motivating users to interact with the device is one of the key success factors of interactive displays.

A particular form of interactive displays are localized displays. These devices provide immediate feedback about the energy usage of a given appliance. Localized displays have not attracted much attention in the literature, although past studies have shown their effectiveness in driving behavioral change. For instance, when consumers were given immediate feedback about washing machine energy usage via an attached control panel, a 21% reduction in energy use was obtained [22]. Likewise, the installation of sensors for each home appliance, and the simultaneous monitoring of total electric power and gas consumption, resulted in a 12% reduction in energy usage [37]. No study has compared different visualization tools (i.e. mobile apps vs. desktop apps, or in-home displays vs. localized displays) vis-à-vis households' preferences, interaction with device or effectiveness, so there is limited evidence to suggest which media combination could work better.

Another aspect that should be introduced in the interactive display, regardless of the specific medium, is the inclusion of anthropomorphized elements, such as spoken messages and/or a human-like face, as there is initial evidence to suggest that they could drive greater energy savings [36, 38]. Reinforcing this finding, evidence shows that when devices are combined with some form of human interaction (e.g. visits of energy delegates) the overall reduction in energy spending is greater [39]. Thus, a combination of personal and impersonal media could drive greater energy savings, but there is limited evidence in this regard. Yet, as delegates visits are costly to implement, a previous segmentation could help identify the customers with potential for greater savings (see 2.4).

A specific type of real time feedback is provided by eco-visualizations [40]. This term refers to ambient devices or "portable art and/or design works that creatively visualize ecologically relevant information using images or occasionally images and sound". For instance, a chord changes color depending on the energy consumption of the household. This type of eco-feedback successfully makes energy visible and prompt a conversation among users about what to do to reduce consumption. Studies [26, 41] have shown that they are good at raising awareness and enhancing motivation but there is limited evidence about the influence on behavior, and the possibility of sustaining users' interest in the long term.

P1. Designers are encouraged to combine overall and localized energy consumption of specific appliances and to anthropomorphize the display and the information provided by including spoken messages or human-like faces, or by combining the feedback received by the interactive display with visits of energy delegates.

2.2. Push vs. pull information.

As it was pointed out in the previous section, devices should incorporate elements that encourage users' interaction with them; engagement with the device is a necessary, but not sufficient condition, for devices to drive energy savings. Thus, a key design feature is whether the device will provide push or pull messages. Pull messages are received only when the user chooses to, whereas push messages are provided through the device automatically.

Interactive devices usually provide pull information but studies show that after an initial period users stop paying attention to it. When given a device, users experience a "honeymoon period" [42], where they engage frequently with it and their energy spending is reduced. Yet, after some months, they tend to engage less with the device and, correspondingly, energy savings are not maintained [43]. Hence, pull messages alone tend to lead to decreased energy savings over time. This suggests that the more the user interacts with the device the greater the energy savings (and vice versa) [9].

In order to gain salience of the device and to maintain energy savings over time, push messages could be delivered by other means (e.g. mobile or email text messages) [44, 45] so as to ensure that users maintain their engagement with the device. Additionally, audio signals could be provided to encourage interaction with the device.

However, abuse of push messages may also lead to infoxication and put users off interacting with the device entirely; thus, it is recommended some degree of customization by users regarding mode of delivery [30]. When correctly implemented, past studies have shown that push messages may counteract the decline in energy savings as time goes by [28].

An additional element that can complement push messages to encourage long-term engagement is the use of prizes rewarding loyalty. This topic will be discussed in section 2.7.

P2. User interaction has been identified as a key determinant of long-term effectiveness of energy conservation interventions. In this regard, pull messages alone do not seem

enough to sustain engagement over time, so they should be combined with push messages and loyalty-based rewards, especially as interaction decays.

2.3. Content of the feedback provided to end users

Most studies on feedback and energy savings have examined the relationship between feedback content and behavioral change. Feedback can be provided as stand-alone information (household energy consumption at some point in time) or as a comparison. In turn, the comparison can be given either with past consumption of the same user, with concurrent consumption of peers, or with a goal set by the user or given by an external party. These forms of providing feedback are not equally effective in driving behavioral change, as explained on the ensuing.

2.3.1. Historical comparison

This type of feedback compares present consumption with past consumption of the same user, be it over a short period (24 hours or weekly) or a long period (monthly). Historical comparison is usually portrayed as a basic feature of the device [9, 20, 35]. However, to the best of our knowledge, there is not any study comparing devices with stand-alone vs. historical comparison and, consequently, there is not solid evidence to discuss the added value of this feature.

It is suggested that by being aware of past consumption and by recalling past activities, users can infer what drives energy consumption upwards. Nonetheless, other studies have shown that users face problems in interpreting visual representations of comparative information with past energy consumption [46] and that their inferences about the reasons for variations in consumption are not very accurate. Thus, there is a need to combine this feature with the disaggregation of the overall consumption by appliances in order to help consumers identify energy saving measures (see section 2.4.).

P3.1. Historical comparison should be provided in a granular form, broken down by appliance.

2.3.2. Normative comparison

Providing a given household with information about the energy consumption of its neighbors or its community is posited as a successful means to encourage behavioral change [47]. However, the effectiveness of normative comparison is inconclusive. Some studies have found that providing comparative feedback drive behavioral change [48-50]. However, in meta-analysis social comparative feedback has been found the least effective form of comparison [51]. Others [9] have concluded that normative comparison encouraged engagement, but did not drive greater savings. In their study, users that logged in the normative comparison logged twice as much as users without this feature, but did not save significantly more energy. These results suggest that social comparison may stir curiosity but not motivate users to change their energy spending habits. Some studies [52] have even found a boomerang effect, where, after being provided with the information of their peers, best performers found a sort of “moral license” to spend more energy.

This conflicting evidence suggest that there are moderating factors that could explain the effectiveness of normative comparisons. For instance, comparison has been found more effective if it is established with people that are similar to the household (residents of the same building or neighborhood) or, even better, friends [9, 53]. Consequently, devices should allow users to customize their social feed so that they can create a more alike group for comparison. Also, it seems important to provide injunctive and not only descriptive norms [54]. Descriptive norms state a norm regarding a given behavior, whereas injunctive norms provide information about whether a behavior is typically approved or disapproved. The inclusion of injunctive norms has been found a driver of other pro-environmental behaviors, such as recycling [55]. Injunctive norms are usually included in the form of smiley or angry emoticons that provide an informal and symbolic sanction or reward of the behavior [20]. The inclusion of such emoticons may drive greater energy savings, but there is limited evidence in the case of interactive displays in support of this suggestion.

Finally, cultural differences may also explain the disparate results. Normative comparison is ill-received in some countries (e.g. UK or Sweden) and celebrated in others (Finland, US, Japan, or Norway) [7, 13, 20, 37, 52, 56, 57]. There is scant research exploring the reasons behind these preferences, so this is an area for further research.

P3.2. Social comparison should be included in devices targeting low performers, but allowing for customization of the peer comparison group. This design parameter should be attuned to cultural norms and local preferences.

2.3.3. Goal comparison

In previous analyses, goal-based feedback significantly increased energy savings [20]. Even when users were not given real-time feedback, the commitment to a specific goal yielded greater savings in gas consumption [22, 58].

For goal comparison to work it is key that the person sets specific goals at the appropriate level in the goal hierarchy: feedback effects on performance are enhanced if feedback is directed to the focal task level [59]. For instance, users should be told to reduce energy by 10% when doing the washing up, rather than being given general messages about fighting climate change or being environmentally friendly.

No differences in energy savings have been found depending on the goal setter: it makes no difference whether the goal is set by the person or set by an external party. Similarly, group goal setting has not proven more effective than individual goal setting, to drive household behavioral change [58]. Yet, the goal must be personally relevant to be effective [22, 59]; one way of increasing relevance is allowing the person to choose the measurement unit (see section 2.5). Studies in other domains (e.g. healthy eating) have shown that explicit directives resulted in more psychological reactance as individuals felt their autonomy was threatened, which compromised the effectiveness of goal setting and goal comparison. Hence, providing some autonomy to households would reduce reactance and increase the effectiveness of goal comparison feedback. Thus, if the device offers some customizable options that can be chosen by the household, users would feel more autonomous and this would increase personal relevance.

Regarding the goal-behavior gap or the goal distance, better results are obtained when households are given difficult goals, as opposed to easy goals [20], in terms of the percentage of energy reduction to be achieved.

Finally, and as said above, it is key to provide information about performance (descriptive norm) together with an evaluation (injunctive norm) [60]. The design of the feedback can facilitate this evaluation; to illustrate if the comparison results are shown in red, users will understand that their performance was not deemed good. In contrast, if the information is provided without evaluation, users may feel that, even when the goal was not met, their performance was fine or, at least, not disapproved. This may reduce motivation to further decrease consumption. This is probably why the combination of goal and incentives/penalties have had higher effect sizes than feedback alone [43].

P3.3. Devices should set focal-task and difficult goals for users, allow users to set personally relevant goals, and provide information about performance against the goal set with an evaluation in the form of emoticons or traffic-light colors.

2.3.4. Negative vs. positive feedback

Another key aspect regarding content is the valence of feedback; feedback can be provided in negative or positive terms. What would work better to drive energy savings? There have been no studies comparing the differential effect of devices providing positive and negative feedback to drive energy conservation. However, some insights can be drawn from energy conservation studies more broadly.

On the one hand, past meta-analysis have shown that creating a cognitive dissonance is one of the most effective strategies to encourage energy conservation [52, 61]. The term "cognitive dissonance" refers to the discomfort experienced by a person when s/he holds two contradictory beliefs or attitudes. Applied to this context, if a user believes that her energy consumption is good and she is proven wrong with the received feedback, this would create a mental discomfort; to reduce this tension the user will probably change her behavior so that eventually a new habit is formed. On the other hand, research has also shown that users seeing positive feedback in the first logins are more likely to log in more [9] and that negative feedback has a debilitating effect on self-efficacy [62] and therefore is rejected by users. Literature on feedback has also found these different reactions to negative feedback: negative feedback may encourage redoubling efforts to achieve a goal or it may lead to withdrawal and abandonment of the goal [63].

The distinct outcomes associated to the valence of feedback have been much studied outside the energy conservation domain. Van Dijk and Kluger found that feedback valence depends on the type of task [62]. They assume that each task demands a different regulatory focus. Tasks triggering promotion focus (e.g. a focus on desires and hopes) will benefit from positive feedback and tasks triggering prevention focus (e.g. focus on duties and safety) with negative feedback. Thus, the regulatory focus moderates the relationship between the valence of feedback and motivation. In turn, the regulatory focus is determined by three factors: (a) the needs that people seek to satisfy—security versus growth, (b) the nature of the goal that people are trying to achieve—ought versus ideal, and (c) the psychological context in which people act—loss/non-loss versus gain/non-gain situations. Security, ought and loss/gain induce a prevention regulatory focus whereas growth, ideal and non-loss/non-gain induce a promotion regulatory focus. When performing a promotion task requiring creativity and open mindedness, one would benefit more from positive feedback than negative feedback. Reversely, when performing a prevention task requiring accuracy and adherence to rules, one benefits more from negative rather than positive feedback. The authors found that positive feedback is a greater

motivator than negative feedback when individuals are promotion-focused, whereas negative feedback motivates more than positive feedback when people are prevention-focused.
Applied to the context of energy conservation this theory suggests that the valence of feedback should be attuned to the way users frame the tasks to be performed to reduce energy. This can only be achieved if users respond to a profiling questionnaire before installing the device.
Cianci and colleagues' work [63] also shows that goal orientation moderates the effectiveness of negative feedback. Individuals with a learning goal orientation tend to react better to negative feedback. A learning orientation is characterized by engagement in discovery or stimulation of one's imagination. In contrast, a performance orientation encourages users to use their skills to persist so that they attain the goal. In this case, individuals view "mistakes and negative feedback as an evaluative threat to the self and to withdraw from the assignment in the face of setbacks in an effort to protect their egos" [63]. If the individual is high on conscientiousness, the effect of being assigned a performance goal is even more acute and the performance is even poorer.
Other studies point at individual-trait differences in the response to negative feedback found that emotional instability led to receive negative feedback with more anger [64]. Also, emotional regulation influences responses to negative feedback: those capable of reappraising the situation performed better after negative feedback than those suppressing negative emotions associated with negative feedback [65]. Finally, research has shown that negative feedback declines intrinsic motivation as it reduces the individual's perceived self-ability [66].
To sum up, individual-related factors explain when to use positive or negative feedback. To customize this feature users should be categorized before installation of the device; a survey with appropriate scales could be used for this purpose.
P3.4. Initial feedback should be positive as it encourages subsequent interaction with the device. It would be necessary to conduct a preliminary categorization of users, so that feedback valence is customized according to their regulatory focus. For those individuals with a promotion focus or a learning orientation, or individuals high in emotional instability, positive feedback could work better, whereas for those with a preventive focus or a performance orientation, negative feedback would be more effective. Yet, more research on feedback valence and its effect on energy savings is necessary to provide a recommendation based on sound evidence.

2.3.5. Design aspects of the user interface for providing information
Regardless of content, design is key to provide the necessary information in a friendly and understandable manner while avoiding the information overload. There is no sound empirical evidence upon which to base a recommendation for design features; some evidences of this can be found in [67], but not based on experimental studies. This is an area where more research is necessary.
Regarding graphics, bars are preferred to curves by users [20]. However, to show the consumption of different appliances, it is suggested that pie charts with texts for further clarification work better [20]. There seems to be an agreement that the use of traffic-light color system to show good or bad performance performs well [9]. For goal comparison, some devices have used ticks and crosses to show whether or not the user is on target to meet a goal [68]. To

our knowledge, no studies have examined the effects on energy savings of using injunctive norms in the form of emoticons or spoken messages.

Moreover, graphs are not the only choice to instruct users about their consumption. Studies using iconic feedback in ambient devices have found that this form of feedback is preferred to numerical and graphic information [41] and that it may lead to greater energy savings than conventional displays [69, 70]. However, other users' surveys concluded that users do not wish ambient technologies incorporated into in-home displays [31]. Thus, whether or not ambient features can improve the effectiveness of devices is a matter for further research.

P3.5 Devices should provide information in a friendly way and avoid overloading. Designers should favor intuitive graphics (preferably pie charts) as they will be more effective, as well as showing performance by means of a traffic-light color code. Further research is needed to assess the effectiveness of ambient signals on end-user behavior.

2.4. Disaggregation level of the consumption data.

Disaggregation or granularity concerns the level at which feedback is offered to users. This is a relevant characteristic to be considered in the devices, i.e. whether feedback includes overall consumption at household level, or whether this is broken down by appliance [35]. There are many benefits of appliance-specific over aggregated-home data [45, 71]. Yet, despite its proven effectiveness in driving energy savings, few devices contain this feature [13].

From the perspective of consumers, whether for domestic or commercial use, the main contributions of granularity is that learning about the sources of energy consumption is enhanced. Meta-analyses have shown that disaggregation is an essential moderator of feedback effect: disaggregation facilitate that users learn what it causes their energy spending so that they can try to minimize it [72]. This learning is impeded when energy consumption is not disaggregated by appliance.

Also, granularity is especially effective in increasing energy savings, when it is accompanied with tips on how to spare more energy when using a given appliance. Disaggregation facilitates automated personalized recommendations and consequently enables the provision of additional information to overcome barriers and foster action [20, 60, 71, 74]. Another advantage of disaggregation is that it provides valuable information that can be applied to the redesign of appliances for energy efficiency.

However, there are limits on the energy savings that can be obtained: not all devices can be switched off easily or completely, and reducing or stopping their use can imply a loss of comfort or compromise the lifestyle of users [68]. For example, a refrigerator is an energy-consuming device that cannot be switched off. In a longitudinal qualitative study of households in UK [42], users became irritated as the device did not differentiate between normal usage, a baseline that cannot be reduced, and extraordinary usage. Users felt that they had reduced their energy wasting practices and that they had no way to improve any further. Some users decide to settle the display in a less conspicuous place and to suspend interaction with the device, due to the ensuing discomfort.

A potential solution to maintain engagement with the device is to conduct a previous audit that assesses the potential for consumption reduction, considering that households without sophisticated items have significantly lower electricity demand and thus less capacity to reduce. Some studies have approached households differently by mapping their practices and their corresponding energy usage first, as a preliminary step to outline customized forms of reducing consumption [34, 75]. As others have rightly pointed out [76], design should be embedded into users' everyday life so that users' actual practices are taken into account. Feedback in the form of alerts, goals, and/or comparisons should be attuned to different profiles to avoid the uneasiness that eventually leads to disengagement with the display.

To carry out this audit, appliances can be grouped into types [67] that are similar in features and user behavior. Group 1 are appliances with a low level of automation and a large number of settings and so the user is frequently needed to supervise operations (e.g. cooker). Group 2 are appliances with high automation and low number of settings (e.g. TV). Group 3 comprises appliances with a high level of automation and several settings, which once chosen do not require or permit user interaction (e.g. washing machine). Group 4 are highly automated appliances with a limited number of settings; the appliance operates continually (e.g. refrigeration) and users can do little to save energy. This audit can serve, at the same time, to provide personalized recommendations to the users (see section 2.6).

The provision of disaggregated feedback presents an added complexity derived from the fact that it requires deploying additional measurement devices to record the consumption of appliances individually, as well as setting-up the communications (e.g. ZigBee or Wifi) enabling the collection of all this information and present it centrally through the in-home display. Given that this implies added costs, the aforementioned consumer profiling may allow identifying those cases for which this intervention may be worthy, considering the expected savings to be achieved. Alternatively, granular information may be provided with a flyer or a card, which could be attached to the display, together with particular suggestions for reducing energy use associated with this appliance.

P4. Designers should provide granular or disaggregated information to users to the extent that it is technically and economically feasible. Yet, to avoid discomfort and uneasiness, designers are encouraged to customize and tailor the devices according to the household's features, based on a previous audit.

2.5. Measurement units.

Feedback can be given in different measurement units: money, watts, emissions, or other yet to be proposed. It is noteworthy that the measurement unit will influence how the environmental problem is perceived (e.g., as a waste of money or as a waste of energy), the motives it activates and the reasoning process that individuals engage in [60]. In some devices this parameter is customizable, as users can choose the units for feedback display, such as dollars or watts, for instance [35] .

There has been a dearth of studies that compare the effectiveness of different forms of measurement. To our knowledge, only Karlin et al [43] tested the effect of presenting the feedback in kilowatts or emissions; they did not find differences on energy savings on the basis of measurement units. Authors explain this finding by the unit used to convert kilowatts into emissions: the figure of emissions saved was very low; this may have led to perceptions of irrelevance which, in turn, reduced motivation to save energy.

Likewise, there are no studies that test the effectiveness of the different ways of displaying such information. Some authors suggest that information should be provided in a way that facilitate "eco-visualization" [53], or said otherwise, in a meaningful, pragmatic, non-abstract

form. To illustrate, instead of giving the amount of emissions saved in CO_2 tons, they propose giving the equivalence with planted trees (e.g. “7000 oaks and counting”).
Extant research on different measurement units and its effects on energy savings and behavioral change is reviewed in turn.

2.5.1. Pecuniary information (€-$).

Feedback in the form of gains and losses of money due to energy use is one of the most researched strategies. Although some studies have suggested strong effects of price signals on reduction of energy consumption, meta-analysis have shown that pecuniary feedback may actually lead to increased energy use, probably due to the aforementioned licensing effect [28] or to no significant effect [43].

To explain these conflicting results, the influence of frame and energy prices has been discussed. First, consistent with behavioral economics, it has been shown that it would work better to frame money feedback as a loss (“by not switching off this appliance you are losing 80 dollars”) rather than gains (“you could save 80 dollars by switching off this appliance”), as people respond better to loss rather than gain frames [16, 77].

Another reason why pecuniary information may not drive behavioral change is because the energy pricing structure and level in most countries leads to minimal gains/losses for residential consumers, which may discourage action [60]. In some countries, high performer households could save at most 3 euros in their bills; such little amount does not motivate households to reduce more energy.

This is why some suggest that pecuniary feedback should be used when the pricing structure is Time-of-Use tariffs or Critical Peak Pricing; with these pricing structures, feedback of consumption in the more pricey hours may encourage shift load [10, 78] and energy savings [35]. Similarly, other authors have proposed to use pecuniary feedback with payment in arrears, progressive block pricing or pay-as-you-go pricing strategies, as these strategies could make users experience more acutely the reward/penalty associated with their own consumption [13, 79]. Yet, there is limited evidence on pricing strategies combined with eco-feedback to sustain a recommendation.

Rewards can be symbolic as the type used in game-like interventions for energy efficiency. They can be implemented via rankings, badges or points that may or may not be linked to a material reward. Game-like interventions have shown positive results, increasing user experience which could lead to greater interaction with the device, raising awareness and knowledge about energy consumption, and resulting in greater energy savings [27].

P5.1. Pecuniary information should be given in the form of losses or lost gains. It should be incorporated into the design depending on the energy pricing structure: if energy prices are flat it may not encourage action; worse it may lead to rebound effects; if energy prices change hourly, feedback on prices may encourage shift load and energy saving behaviors. Also, pecuniary information could be included if the payment mode makes this information more relevant to users as they can see a stronger link between their energy consumption and their bill.

2.5.2. Energy consumptions (kW-kWh).

It is usually a default option in most displays, probably because the apps are also used for billing purposes. It should be understood as the most neutral measurement and may reinforce the abstractness of energy, jeopardizing motivation for improvement. It is the least preferred by users [31] as it is difficult to decipher [67]; likewise, according to existing research, it is the least effective feedback to drive driving energy savings. However, when combined with granular information it may facilitate learning [73].

P5.2. Energy consumption (kilowatts-kWh) is the default measurement in most devices as apps are used for billing purposes. Yet, their effect *per se* on energy savings is weak.

2.5.3. Emissions and/or other measures of environmental impact.

Information linked to emissions may stimulate environmental concerns. Regarding climate change, several authors [80-82] use the Construal Level Theory (CLT) of psychological distance [83] to highlight that climate change is perceived to be distant on all the dimensions: spatial or geographical distance; temporal distance; social distance or distance between the perceiver and a social target and hypothetical distance/uncertainty. Therefore, they defend the usefulness of emphasizing the risk and potentially very serious but distant impacts of climate change to promote sustainable behaviors, as well as the usefulness of communication techniques designed to reduce psychological distance.

In this line, information about emissions is a form of abstract information and may not help users focus on task-related goals. Even when users stated a preference for feedback display in the form of CO_2 emissions, in practice they did not use the feature of the display, partly because they did not understand what the emissions entailed, partly because they did not feel the information was useful for them [31]. Providing this information in a less abstract form could encourage greater savings; for instance, comparing the emissions saved with planted trees as suggested by Petkov et al [53].

Yet, designers could think of other ways of providing relevant and specific information that may drive behavioral change. For instance, a recent study provided the information about emissions as health-related information; in particular, users were given the pounds of air pollutant emissions and a listing of health consequences, namely, childhood asthma and cancer. This health-based information frame induced persistent energy savings behavior of 8-10% over a 100-day period, whereas the more traditional cost savings frame drove sharp attenuation of intervention effects after 2 weeks with no significant savings versus control after 7 weeks. These results show that energy conservation could be long-lived with health framing; moreover, this framing can be used as a strategy to overcome behavioral barriers, especially in settings where price-based policies may not be feasible or effective [84].

To sum up, designers should provide information in other ways than dollars and kilowatts, as these have not proven effective enough to drive sustained behavioral change. This information should be as specific as possible, using analogies that help visualize the impact of energy consumption. Also, this information should be made as relevant as possible. For instance, providing feedback in the form of health impact could facilitate energy savings.

P5.3. Information about energy consumption should be as relevant as possible (environmental or health-related impacts), using easier-to-understand analogies that help visualize the impact of energy consumption.

2.6. Problem solving.

Device feedback really works only if households have a clear idea on what they can do about their consumption (in line with the issues of injunctive feedback and disaggregated feedback discussed above). Results about the effectiveness of tips and suggestions are mixed. Some studies have found no use or even counterproductive effects of providing this additional information, with only limited exceptions [52].

There are two main problem-solving strategies: audits, discussed in section 2.4, or tailored recommendations and general tips. As aforementioned, specific and clear guidelines are preferred to general educational messages for reducing energy, as the latter have had a non-significant effect in energy conservation [85]. Personalized recommendations (e.g. plug out your TV and you will save this amount of energy) have yielded significant effects in energy reductions [28, 33, 58]. It should be borne in mind that there is not "one-size fits all" feedback; users' motivations and beliefs have to be taken into account and feedback should be tailored according to them [28]. Besides, feedback preferences may vary according to regional differences, so it is relevant to consider the cultural context.

P6. The use of general tips or recommendations for energy savings seem of little use. Instead, designers are encouraged to customize tips to the energy consumption profile of the user, based on audits.

2.7. Consequences of feedback

Above we have discussed that feedback information in the form of potential dollars saved/spent. In addition to potential billing savings, authors have defended the need for other rewards as a result of feedback. Rewards and penalties could be of two kinds: material or symbolic. There has been a paucity of empirical studies addressing the effect of rewards or penalties on energy use. Stern discusses the interactive effects of information and material incentives in pro-environmental consumer behavior [86]. The author concludes that both levers fulfil different functions and, when properly deployed, they can have synergistic effects on behavior.

Probably it is more feasible to implement rewards than penalties. Material rewards could consist of additional discounts on bills or points to be redeemed in affiliate stores or traded in for gifts. Also, rewards may encourage interaction with the device: users receiving rewards in the initial interactions with the device are more likely to use it [9]; thus, the use of rewards at the initial stages may increase engagement with the device [9, 28, 87].

Although the decision of including material rewards or penalties is beyond the device designer, it is possible to add gamelike rewards and symbolic rewards as drivers of behavioral change [88, 89], as discussed in section 2.3 (use of emoticons, traffic-color system to provide feedback, use of ticks and cross to show performance, inter alia).

P7. Designers must take advantage on the use of incentives to promote energy conservation. These incentives may consist of financial rewards or gamification/symbolic prices, supported by friendly and personally relevant communication.

2.8. Design for the whole family

Interactive displays are placed in households where different individuals cohabit. This point is not trivial: a challenge for the displays design is that they should take into account the profile and preferences of these different individuals that may certainly hold distinct attitudes and values [68]. However, this fact has seldom been taken into account in past studies.

Devices should be designed in such a way that they engage all users in the commitment to reducing consumption [90]; otherwise the energy savings of one member may be offset by the energy spending of another one. Worse, it has been documented that arguments among members due to the device often occur, as the energy consumption was interpreted by some family members as a form of surveillance on them [68].

If the device provides granular information, different goals can be set for different family members. For instance, children could be given responsibility to reducing the consumption associated to the appliances they often use or entrusted with energy savings in their rooms. Also, visual icons and texts should be designed so that they appeal to different age and education profiles. Nonetheless, there is no evidence to sustain this suggestion. Much research is needed to understand what features facilitate energy savings of different family members.

P8. Devices should be designed for different family members, ensuring that its elements appeal to different age and educational profiles and that different family members are responsible for energy conservation goals.

2.9. Aesthetic appeals

There is a growing concern about the benefits of applying aesthetic elements and principles in information visualization solutions [91]. Aesthetics is fundamental in two dimensions: external (aesthetics of the device) and internal (aesthetics of the elements used to provide feedback - colors, brightness and text).

Regarding the external dimension, research has shown that most devices are not integrated effectively into the décor [41]. If devices are not aesthetically appealing, users tend to place them in a hidden place at home which limits interaction with the device, reducing in turn the possibility of receiving the eco-feedback. This thwarts the potential behavioral change [68].

Regarding the internal dimension, applying aesthetic principles in visual communication to device design can help reduce cognitive load, avoid eye fatigue, and encourage communication efficiency. There are some evidences of the relationship between aesthetic and the efficiency/effectiveness of retrieval tasks, with different data visualization techniques [92], in the way that a favorable and unfavorable aesthetic ranking fits with metrics of task abandonment and erroneous response to devices.

In the relation between color and home devices design, it must be taken into account that human perception varies on the basis of on three attributes: hue (i.e., color), value (i.e., light vs. dark), and brightness (i.e., saturation). There are limitations on humans perceiving brightness and color on information displays. The simultaneous contrast effect caused by the perceptive mechanisms that produce lightness constancy and lateral inhibition can result in judgment errors when reading information displayed using different brightness (value) levels [93]. These physical conditions could show that maintaining a constant level in terms of luminance intensity in the devices may be desirable, although there is no direct evidence to support their impact on greater energy savings.

Similarly, due to color constancy, people perceive color differently under different combinations or in different environments. It is argued that human eye finds nature's colors more harmonious than other ones, so the use of greens, blues and browns for information displays would be desirable [92]. These colors should be considered in standby mode in devices while traffic-light color system is desirable to show good or bad performance. Color is the first attribute mentioned by users in studies on user experience, which shows that users associate their affective experience of the display designs with the chosen color palettes [41].

The use of imagery and the visualization of information (for example, by analogies or metaphors) can help improve the integration of devices and the information displayed with the decoration and the environment. The use of pictorial forms instead of text allows to relax certain requirements regarding the luminosity and contrast [93]. This can benefit a more harmonious integration into decor. As it was mentioned before regarding colors, the most usual metaphors to represent the information iconically come from nature. Although the most used symbols (e.g. trees) are universally recognized and interpretable, the relevance of choosing an appropriate representation to eliminate the vagueness of abstract data is a condition for the effectiveness of device.

There is no evidence about to what degree fine art visualizations are useful as opposed to the traditional design-based ambient light monitors embedded into home devices. However, some evidence suggests that art can provide a startling situation to create increased situational energy awareness [40]. More research is needed to understand how to implement eco-visualizations aimed at creating collective consciousness and simultaneously influencing individual behavior.

P9. As aesthetics affects usability, aesthetics should become an integral part of designing data visualization devices. The possibility to customize colors in the display design is relevant to the emotional engagement of users in domestic environment, so a previous audit to personalize design could lead to greater engagement with the device and better user experience. Much additional evidence is needed to disambiguate the effect of aesthetic components on energy savings.

2.10. Ensure users' trust and privacy

Trust in the source providing the information is essential to consider eco-feedback reliable [20]. Despite recognizing the importance of trust, few studies have addressed this aspect empirically [94]. The main conclusion of these studies is that users distrust smart meter information as they did not believe was accurate enough [21]. A recent survey conducted by the European Commission [95] offers a revealing overview of the scores on consumers' trust for a wide range of product and services markets. A specific item measures the extent to which consumers are confident that suppliers or retailers. The electricity service ranks second from the bottom at European level (UE28), showing a high level of mistrusts in power utilities.

Other research has shown that when the entity demanding energy savings is perceived as authentic and their motives are deemed selfless, trust increases, and so does energy conservation [3]. Nonprofit and community-based firms are, thus, considered more trustworthy than commercial organizations. In this sense, Burchell et al. [96] argue that participation in programs of local or community scope provides greater confidence and offer the potential to reach new segments of households who might engage with energy consumption feedback. Although this last point does not refer specifically to the design of the device, it is important to highlight it as a relevant issue. One way to signal trust is to engage in partnerships with other trustworthy actors. Also, devices should be justified as part of a broader strategy for energy

conservation, environmental protection, local or social development (i.e., Smart communities or local energy communities using the term recently incorporated by UE legislation).
P10.1 Trust can be created by incorporating third-party endorsement in the device and/or through a communication campaign aimed at explaining the linkage with more ambitious initiatives for environmental protection, local or social development.

Another key issue for device designer is privacy. Feedback displays do not just visualize consumption: they document household activities and latent household routines, etc. and this could affect whether households accept having a device at home or the interaction with the display. Thus, it is crucial to determine what are the bounds of privacy for users in the presentation or sharing of detailed energy [97]. With interactive devices, utility companies could know what appliances are being used, or even make decisions to turn off appliances without the consent of an owner. Thus, privacy concerns arise in relation to load and feedback disaggregation [98].

Actual experiences have shown how privacy concerns can be a major barrier for using and interacting with interactive devices. For instance, data security and privacy was a major reason for the introduction of a clause allowing consumers to opt-out of the installation of a smart meter [99], thus effectively hampering energy efficiency programs on these users. Under European legislation, metered data is considered personal data, thus subject to the corresponding protections under the General Data Protection Regulation (GDPR) that came into force in 2018 [100]. Moreover, the recast European Electricity Directive, which is part of the Clean Energy Package, states that any party wishing to access metered data from end consumers must have users' explicit consent [101].
P10.2. In-home displays should include the privacy policy and specify the use given to the different levels of disaggregation of information, express consent and revocable consent. Stricter policies may be necessary in certain cultural settings.

3. Conclusion

This paper has reviewed existing research on feedback, focusing especially on interactive devices, to eventually propose an architectural model for device design. In particular, the review has led to propose ten key parameters that should be taken into account by device designers and suggested recommendations to apply them. Moreover, the review has also led to identify key areas where much research is needed before a sound recommendation can be made.
There are several conclusions about the design of the devices that can be drawn from the review of the literature, which show a clear potential impact on energy savings. First, as discussed in several parameters, the device design should be customized This, in turn, demands a preliminary survey of users. A description of day-to-day household behavior, the analysis of household disposition towards energy savings, the identification of tariff and its composition for each user are necessary to adapt the design of the device and the messages sent through the device to households. Additionally, a preliminary audit of household energy consumption is needed to understand points of energy use and to determine how much can be reduced in a given household. This audit, together with the corresponding sensors and home communication network when expected savings justify the added costs, would facilitate granularity or

disaggregated information to users (by appliance) and it would allow providing tailored advice. This prior audit can also inform the user profile in terms of regulatory focus and concerns (pecuniary or environmental), both key aspects to provide tailored advice.

Second, it has been highlighted in different parameters that maintaining motivation is key so that users interact with the device. Thus, device design should take into account characteristics and functionalities. This would comprise both the design of the physical device itself (when applicable) as well as the user interface, including features such as aesthetics, alerts and positive feedback to promote interaction with the devices. In this line, allowing households to choose color features is particularly relevant in the domestic environment where coherence with the surrounding aesthetic choices is highly valued. Besides, the use of colors and imagery could make information more understandable and personally relevant to avoid information overload and to ensure sensorial fit.

Finally, since eco-feedback programs necessarily rely on metered data, it must be ensured that users' do not oppose these programs due to trust and privacy concerns. In order to prevent this from happening, consumers should be provided with information on the far-reaching goals of the initiatives in terms of environmental impact or social development, as well as the data privacy policy and rights to know the intended use of the data, or express and revoke consent.

This review has also unveiled areas where further research is needed. First, it is apparent that if users do not interact with the device, the possibilities of energy savings are curtailed. More research is necessary to identify cost-effective mechanisms to encourage users to interact with the device. Specifically, more research is needed to understand what type of alerts may work better to encourage interaction with the device. Also, it should be explored the effect of localized displays on energy savings; as they cannot be ignored while using appliances they may encourage greater savings.

Regarding interventions, future studies should examine the differential impact on energy savings of goals formulated at different levels of abstraction. Equally, the interaction between goal formulation and the individual's regulatory focus has not been tested in the context of energy conservation. In relation to feedback on performance, another aspect deserving further attention is when and how provide negative versus positive valence. Past studies have provided reasons to sustain that both types of feedback may work so more research is needed to establish when, how and for whom each of them should be used. Likewise, more research is needed to understand how the use of rewards and penalties impinge on the interaction with the device and on behavioral change.

An area that has received little attention is the differential impact of pictorial design on savings, as well as the influence of specific ways of depicting the feedback in terms of colors, type of graphics, etc. Equally, aesthetic aspects and their influence of energy savings have not been studied, even though they have found to shape human action in other domains.

Finally, the review has provided many instances of how cultural groups and social groups respond differently to design. Thus, further research is necessary to understand how to implement the identified parameters across countries and social groups to optimize the potential results of interactive displays.

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References

[1] European Environment Agency, "Annual Indicator Report Series 2017," No 21/2017, 2017.

[2] L. X. W. Hesselink and E. J. L. Chappin, "Adoption of energy efficient technologies by households â€“ Barriers, policies and agent-based modelling studies," *Renewable and Sustainable Energy Reviews*, vol. 99, pp. 29, 2019.

[3] E. R. Frederiks, K. Stenner, and E. V. Hobman, "Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1385, 2015.

[4] L. Steg, "Promoting household energy conservation," *Energy Policy*, vol. 36, pp. 4449-4453, 2008.

[5] D. K. Ehrhardt-Martinez K, Laitner S., "Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities," American Council for an Energy-Efficient Economy, Washington DC 2010.

[6] K. Zhou and S. Yang, "Understanding household energy consumption behavior: The contribution of energy big data analytics," *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 810, 2016.

[7] F. Shariatzadeh, P. Mandal, and A. K. Srivastava, "Demand response for sustainable energy systems: A review, application and implementation strategy," *Renewable & Sustainable Energy Reviews*, vol. 45, pp. 343-350, 2015.

[8] C. McKerracher and J. Torriti, "Energy consumption feedback in perspective: Integrating Australian data to meta-analyses on in-home displays," *Energy Efficiency*, vol. 6, pp. 387, 2013.

[9] R. K. Jain, J. E. Taylor, and G. Peschiera, "Assessing eco-feedback interface usage and design to drive energy efficiency in buildings," *Energy and Buildings*, vol. 48, pp. 8, 2012.

[10] B. Zhou, W. Li, K. W. Chan, Y. Cao, Y. Kuang, X. Liu, and X. Wang, "Smart home energy management systems: Concept, configurations, and scheduling strategies," *Renewable and Sustainable Energy Reviews*, vol. 61, pp. 30, 2016.

[11] J. Burgess and M. Nye, "Re-materialising energy use through transparent monitoring systems," *Energy Policy*, vol. 36, pp. 4454-4459, 2008.

[12] J. Froehlich, "Promoting energy efficient behaviors in the home through feedback: The role of human-computer interaction," presented at HCIC Workshop, 2009.

[13] S. Darby, "The effectiveness of feedback on energy consumption - A review for DEFRA of the literature on meering, billing and direct displays," Environmental Change Institute. University of Oxford 2006.

[14] L. Broms, C. Katzeff, M. Bång, Å. Nyblom, I. H. Sara, and K. Ehrnberger, "Coffee maker patterns and the design of energy feedback artefacts," presented at 8th ACM conference on designing interactive systems, 2010.

[15] F. Gangale, A. Mengolini, and I. Onyeji, "Consumer engagement: An insight from smart grid projects in Europe," *Energy Policy*, vol. 60, pp. 621, 2013.

[16] S. Bager and L. Mundaca, "Making ˜Smart Meters" smarter? Insights from a behavioural economics pilot field experiment in Copenhagen, Denmark," *Energy Research and Social Science*, vol. 28, pp. 68, 2017.

[17] S. Sorrell, "Reducing energy demand: A review of issues, challenges and approaches," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 74, 2015.

[18] K. Ehrhardt-Martinez, "Engaging, enabling and empowering people. The savings potential of behavioral strategies & enabling technologies.," EIA Energy Conference Presentations https://www.eia.gov/conference/2017/pdf/presentations/karen_ehrhardt_martinez.pdf, 2017.

[19] P. Xu, J. Shen, X. Zhang, X. Zhao, and Y. Qian, "Case Study of Smart Meter and In-home Display for Residential Behavior Change in Shanghai, China," *Energy Procedia*, vol. 75, pp. 2694, 2015.

[20] D. Vine, L. Buys, and P. Morris, "The Effectiveness of Energy Feedback for Conservation and Peak Demand: A Literature Review," *Open Journal of Energy Efficiency*, vol. 2, 7-15, 2013.

[21] K. Buchanan, R. Russo, and B. Anderson, "Feeding back about eco-feedback: How do consumers use and respond to energy monitors?" *Energy Policy*, vol. 73, pp. 138, 2014.

[22] L. T. McCalley and C. J. H. Midden, "Energy conservation through product-integrated feedback: The roles of goal-setting and social orientation," *Journal of Economic Psychology*, vol. 23, pp. 589, 2002.

[23] K. Matsui, H. Ochiai, and Y. Yamagata, "Feedback on electricity usage for home energy management: A social experiment in a local village of cold region," *Applied Energy*, vol. 120, pp. 159, 2014.

[24] A. Kavousian, R. Rajagopal, and M. Fischer, "Determinants of residential electricity consumption: Using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants' behavior," *Energy*, vol. 55, pp. 184-194, 2013.

[25] K. Trinh and G. A. Jamieson, "Feedback design heuristics for energy conservation," *Ergonomics in Design*, vol. 22, pp. 13, 2014.

[26] L. Bartram, "Design Challenges and Opportunities for Eco-Feedback in the Home," *IEEE Computer Graphics and Applications*, vol. 35, pp. 52, 2015.

[27] D. Johnson, E. Horton, R. Mulcahy, and M. Foth, "Gamification and serious games within the domain of domestic energy consumption: A systematic review," *Renewable and Sustainable Energy Reviews*, vol. 73, pp. 249, 2017.

[28] M. A. Delmas, M. Fischlein, and O. I. Asensio, "Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975 to 2012," *Energy Policy*, vol. 61, pp. 729, 2013.

[29] J. Schleich, M. Klobasa, S. Gölz, and M. Brunner, "Effects of feedback on residential electricity demand-findings from a field trial in Austria," *Energy Policy*, vol. 61, pp. 1097, 2013.

[30] I. Vassileva, E. Dahlquist, F. Wallin, and J. Campillo, "Energy consumption feedback devices' impact evaluation on domestic energy use," *Applied Energy*, vol. 106, pp. 314, 2013.

[31] G. Fitzpatrick and G. Smith, "Technology-enabled feedback on domestic energy consumption: Articulating a set of design concerns," *IEEE Pervasive Computing*, vol. 8, pp. 37, 2009.

[32] M. A. Alahmad, P. G. Wheeler, A. Schwer, J. Eiden, and A. Brumbaugh, "A comparative study of three feedback devices for residential real-time energy monitoring," *IEEE Transactions on Industrial Electronics*, vol. 59, pp. 2002, 2012.

[33] A. Kamilaris, J. Neovino, S. Kondepudi, and B. Kalluri, "A case study on the individual energy use of personal computers in an office setting and assessment of various feedback types toward energy savings," *Energy and Buildings*, vol. 104, pp. 73, 2015.

[34] D. Parker, D. Hoak, A. Meier, and R. Brown, "How much energy are we using? Potential of residential energy demand feedback devices," presented at 2006 Summer Study on Energy Efficiency in Buildings, Asilomar, CA, 2006.

[35] A. Faruqui, S. Sergici, and A. Sharif, "The impact of informational feedback on energy consumption-A survey of the experimental evidence," *Energy*, vol. 35, pp. 1598, 2010.

[36] S. Vossen, J. Ham, and C. Midden, "What makes social feedback from a robot work? Disentangling the effect of speech, physical appearance and evaluation," in *Lecture Notes in*

Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 6137 LNCS, 2010, pp. 52.

[37] T. Ueno, R. Inada, O. Saeki, and K. Tsuji, "Effectiveness of displaying energy consumption data in residential houses. Analysis on how the residents respond.," presented at 2005 summer study of the European Council for an energy efficient economy, Stockholm, 2005.

[38] J. Pyrko, "Energy saving targets! - Tested in households in the Swedish largest electricity saving experiment," presented at 2013 summer study of the European Council for an energy efficient economy, Cote d'Azur, Frankrike, 2013.

[39] A. Emeakaroha, C. S. Ang, Y. Yan, and T. Hopthrow, "A persuasive feedback support system for energy conservation and carbon emission reduction in campus residential buildings," *Energy and Buildings*, vol. 82, pp. 719, 2014.

[40] T. G. Holmes, "Eco-visualization: Combining art and technology to reduce energy consumption," *Creativity and Cognition 2007, CC2007 - Seeding Creativity: Tools, Media, and Environments*, pp. 153, 2007.

[41] J. Rodgers and L. Bartram, "Exploring ambient and artistic visualization for residential energy use feedback," *IEEE Transactions on Visualization and Computer Graphics*, vol. 17, pp. 2489, 2011.

[42] T. Hargreaves, M. Nye, and J. Burgess, "Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term," *Energy Policy*, vol. 52, pp. 126, 2013.

[43] B. Karlin, J. F. Zinger, and R. Ford, "The effects of feedback on energy conservation: A meta-analysis," *Psychological Bulletin*, vol. 141, pp. 1205, 2015.

[44] M. Weiss, F. Mattern, T. Graml, T. Staake, and E. Fleisch, "Handy feedback: Connecting smart meters with mobile phones," presented at MUM 2009 - Proceedings of the 8th International Conference on Mobile and Ubiquitous Multimedia, 2009.

[45] J. Froehlich, E. Larson, S. Gupta, G. Cohn, M. S. Reynolds, and S. N. Patel, "Disaggregated End-Use Energy Sensing for the Smart Grid," *Ieee Pervasive Computing*, vol. 10, pp. 28-39, 2011.

[46] C. Egan, W. Kempton, A. Eide, D. Lord, and C. Payne, "How Customers Interpret and Use Comparative Graphics of Their Energy Use," presented at 1996 ACEEE summer study on energy efficiency in buildings, Berkeley, CA, 1996.

[47] D. Geelen, A. Reinders, and D. Keyson, "Empowering the end-user in smart grids: Recommendations for the design of products and services," *Energy Policy*, vol. 61, pp. 151, 2013.

[48] R. K. Jain, R. Gulbinas, J. E. Taylor, and P. J. Culligan, "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," *Energy and Buildings*, vol. 66, pp. 119, 2013.

[49] P. W. Schultz, M. Estrada, J. Schmitt, R. Sokoloski, and N. Silva-Send, "Using in-home displays to provide smart meter feedback about household electricity consumption: A randomized control trial comparing kilowatts, cost, and social norms," *Energy*, vol. 90, pp. 351, 2015.

[50] I. Ayres, S. Raseman, and A. Shih, "Evidence from Two Large Field Experiments that Peer Comparison Feedback Can Reduce Residential Energy Usage," *The Journal of Law, Economics, and Organization*, vol. 29, pp. 992, 2013.

[51] W. Abrahamse and L. Steg, "Social influence approaches to encourage resource conservation: A meta-analysis," *Global Environmental Change*, vol. 23, pp. 1773, 2013.

[52] C. Fischer, "Feedback on household electricity consumption: A tool for saving energy?" *Energy Efficiency*, vol. 1, pp. 79, 2008.

[53] P. Petkov, F. Köbler, M. Foth, and H. Krcmar, "Motivating domestic energy conservation through comparative, community-based feedback in mobile and social media," presented at 5th International Conference on Communities and Technologies, Brisbane, Australia, 2011.

[54] R. B. Cialdini, "The science of persuasion," *Scientific American Mind*, vol. 14 (1), pp. 70-77, 2004.

[55] R. B. Cialdini, R. R. Reno, and C. A. Kallgren, "A Focus Theory Of Normative Conduct - Recycling The Concept Of Norms To Reduce Littering In Public Places," *Journal Of Personality And Social Psychology*, vol. 58, pp. 1015-1026, 1990.

[56] M. Haakana, L. Sillanpää, and M. Talsi, "The effect of feedback and focused advice on household energy consumption," presented at Paper presented at the Summer Study of the European Council for an Energy Efficient Economy, 1997.

[57] IEA, "Time of use pricing and energy use for demand management delivery, Subtask 1 Report: Smaller customer energy saving by end use monitoring and feedback.," International Energy Agency, demand-side management programme, Task XI http://dsm.iea.org/Files/Tasks/Task%20XI%20-%20Time %20of%20Use%20Pricing%20and%20Energy%20Use% 20for%20Demand%20Management%20Delivery/Reports/ Subtask1Report12May05.pdf, 2005.

[58] W. Abrahamse, L. Steg, C. Vlek, and T. Rothengatter, "The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents," *Journal of Environmental Psychology*, vol. 27, pp. 265, 2007.

[59] L. T. McCalley, P. W. de Vries, and C. J. H. Midden, "Consumer response to product-integrated energy feedback: Behavior, goal level shifts, and energy conservation," *Environment and Behavior*, vol. 43, pp. 525, 2011.

[60] K. Buchanan, R. Russo, and B. Anderson, "The question of energy reduction: The problem(s) with feedback," *Energy Policy*, vol. 77, pp. 89, 2015.

[61] R. Osbaldiston and J. P. Schott, "Environmental sustainability and behavioral science: Meta-analysis of proenvironmental behavior experiments," *Environment and Behavior*, vol. 44, pp. 257, 2012.

[62] D. Van Dijk and A. N. Kluger, "Task type as a moderator of positive/negative feedback effects on motivation and performance: A regulatory focus perspective," *Journal of Organizational Behavior*, vol. 32, pp. 1084, 2011.

[63] A. M. Cianci, H. J. Klein, and G. H. Seijts, "The effect of negative feedback on tension and subsequent performance: The main and interactive effects of goal content and conscientiousness," *Journal of Applied Psychology*, vol. 95, pp. 618, 2010.

[64] J. Niemann, B. Wisse, D. Rus, N. W. Van Yperen, and K. Sassenberg, "Anger and attitudinal reactions to negative feedback: The effects of emotional instability and power," *Motivation and Emotion*, vol. 38, pp. 687, 2014.

[65] J. N. Raftery and G. Y. Bizer, "Negative feedback and performance: The moderating effect of emotion regulation," *Personality and Individual Differences*, vol. 47, pp. 481, 2009.

[66] A. F. Weidinger, B. Spinath, and R. Steinmayr, "Why does intrinsic motivation decline following negative feedback? The mediating role of ability self-concept and its moderation by goal orientations," *Learning and Individual Differences*, vol. 47, pp. 117, 2016.

[67] G. Wood and M. Newborough, "Energy-use information transfer for intelligent homes: Enabling energy conservation with central and local displays," *Energy and Buildings*, vol. 39, pp. 495, 2007.

[68] T. Hargreaves, M. Nye, and J. Burgess, "Making energy visible: A qualitative field study of how householders interact with feedback from smart energy monitors," *Energy Policy*, vol. 38, pp. 6111, 2010.

[69] J. Ham and C. Midden, "Ambient persuasive technology needs little cognitive effort: The differential effects of cognitive load on lighting feedback versus factual feedback," in *Lecture*

Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 6137 LNCS, 2010, pp. 132.

[70] T. Kim, H. Hong, and B. Magerko, "Designing for persuasion: Toward ambient eco-visualization for awareness," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 6137 LNCS, 2010, pp. 106.

[71] K. Carrie Armel, A. Gupta, G. Shrimali, and A. Albert, "Is disaggregation the holy grail of energy efficiency? The case of electricity," *Energy Policy*, vol. 52, pp. 213, 2013.

[72] J. Paay, J. Kjeldskov, M. B. Skov, D. Lund, T. Madsen, and M. Nielsen, "Design of an appliance level eco-feedback display for domestic electricity consumption," presented at Proceedings of the 26th Australian Computer-Human Interaction Conference, OzCHI 2014, 2014.

[73] T. Krishnamurti, A. L. Davis, G. Wong-Parodi, J. Wang, and C. Canfield, "Creating an in-home display: Experimental evidence and guidelines for design," *Applied Energy*, vol. 108, pp. 448, 2013.

[74] P. Chakravarty and A. Gupta, "Impact of energy disaggregation on consumer behavior," presented at Behavior, Energy and Climate Change, Sacramento, CA, 2013.

[75] S. Pink, K. L. Mackley, V. Mitchell, M. Hanratty, C. Escobar-Tello, T. Bhamra, and R. Morosanu, "Applying the lens of sensory ethnography to sustainable HCI," *ACM Transactions on Computer-Human Interaction*, vol. 20, 2013.

[76] Y. Strengers, "Designing eco-feedback systems for everyday life," presented at Conference on Human Factors in Computing Systems - Proceedings, 2011.

[77] P. C. Stern, "Contributions of Psychology to Limiting Climate Change," *American Psychologist*, vol. 66, pp. 303, 2011.

[78] H. Saele and O. S. Grande, "Demand response from household customers: Experiences from a pilot study in Norway," *IEEE Transactions on Smart Grid*, vol. 2, pp. 90, 2011.

[79] S. Darby, "Energy feedback in buildings: improving the infrastructure for demand reduction," *Building Research And Information*, vol. 36, pp. 499-508, 2008.

[80] T. L. Milfont, "Global warming, climate change and human psychology," in *Psychological Approaches to Sustainability: Current Trends in Theory, Research and Applications*: New York: Nova Science, 2010, pp. 19-42.

[81] A. Spence, W. Poortinga, and N. Pidgeon, "The Psychological Distance of Climate Change," *Risk Analysis*, vol. 32, pp. 957-972, 2012.

[82] R. I. McDonald, H. Y. Chai, and B. R. Newell, "Personal experience and the 'psychological distance' of climate change: An integrative review," *Journal of Environmental Psychology*, vol. 44, pp. 109, 2015.

[83] Y. Trope and N. Liberman, "Temporal Construal," *Psychological Review*, vol. 110, pp. 403, 2003.

[84] O. I. Asensio and M. A. Delmas, "The dynamics of behavior change: Evidence from energy conservation," *Journal of Economic Behavior and Organization*, vol. 126, pp. 196, 2016.

[85] M. A. R. Lopes, C. H. Antunes, and N. Martins, "Energy behaviours as promoters of energy efficiency: A 21st century review," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 4095, 2012.

[86] P. C. Stern, "Information, incentives, and proenvironmental consumer behavior," *Journal of Consumer Policy*, vol. 22, pp. 461, 1999.

[87] R. Gulbinas, R. K. Jain, J. E. Taylor, G. Peschiera, and M. Golparvar-Fard, "Network ecoinformatics: Development of a social ecofeedback system to drive energy efficiency in residential buildings," *Journal of Computing in Civil Engineering*, vol. 28, pp. 89, 2014.

[88] M. Bang, A. Gustafsson, and C. Katzeff, "Promoting new patterns in household energy consumption with pervasive learning games," in *Lecture Notes in Computer Science (including*

subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 4744 LNCS, 2007, pp. 55.

[89] J. Froehlich, L. Findlater, and J. Landay, "The design of eco-feedback technology," presented at Conference on Human Factors in Computing Systems - Proceedings, 2010.

[90] M. S. Horn, P. Davis, A. K. Hubbard, D. Keifert, Z. A. Leong, and I. C. Olson, "Learning sustainability: Families, learning, and next-generation eco-feedback technology," presented at Proceedings of IDC 2011 - 10th International Conference on Interaction Design and Children, 2011.

[91] M. Promann, S. Wei, Z. C. Qian, and Y. V. Chen, "The Role of Aesthetics and Perception in Raising Situation Awareness: Lessons from SpringRain," *International Journal of Human-Computer Interaction*, vol. 32, pp. 308, 2016.

[92] N. Cawthon and A. V. Moere, "The effect of aesthetic on the usability of data visualization," presented at Proceedings of the International Conference on Information Visualisation, 2007.

[93] C. Ware, *Information Visualization: Perception for Design: Second Edition*, 2004.

[94] N. Simcock, S. MacGregor, P. Catney, A. Dobson, M. Ormerod, Z. Robinson, S. Ross, S. Royston, and S. Marie Hall, "Factors influencing perceptions of domestic energy information: Content, source and process," *Energy Policy*, vol. 65, pp. 455, 2014.

[95] European Commission, "Monitoring Consumer Markets in the European Union 2017. Final Report - Part I," 2018.

[96] K. Burchell, R. Rettie, and T. C. Roberts, "Householder engagement with energy consumption feedback: The role of community action and communications," *Energy Policy*, vol. 88, pp. 178, 2016.

[97] A. Liu, D. Giurco, and P. Mukheibir, "Motivating metrics for household water-use feedback," *Resources, Conservation and Recycling*, vol. 103, pp. 29, 2015.

[98] S. Makonin, F. Popowich, and B. Gill, "The cognitive power meter: Looking beyond the smart meter," presented at Canadian Conference on Electrical and Computer Engineering, 2013.

[99] European Commission, "Commission staff working document: Cost-benefit analyses & state of play of smart metering deployment in the EU-27. Accompanying the document Report from the Commission Benchmarking smart metering deployment in the EU-27 with a focus on electricity," SWD(2014) 189 final, Brussels, 17.6 2014.

[100] European Commission, "Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation)," 2016.

[101] European Commission, "Proposal for a Directive of the European Parliament and of the Council on common rules for the internal market in electricity (recast). CORRIGENDUM," COM(2016) 864 final/2. 2016/0380 (COD), Brussels, 23.2. 2017.