Energy feedback to domestic consumers: An evidence review for the Smart Energy Research Lab

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Ellen Webborn
UCL Energy Institute, University College London (UCL)
London, UK
e.webborn@ucl.ac.uk

Executive summary

The purpose of this evidence review is to inform a future energy advice service for domestic consumers (likely to be delivered as part of the **Smart Energy Research Lab** (SERL)[1]) about what types of feedback have been trialled in the past, and what can be learned from these trials. Preliminary recommendations are offered in the next section in the executive summary, ahead of the more detailed review of different aspects of energy feedback and advice.

In the context of this review, we define the term **(energy) feedback** to consist of two distinct types of information: **consumption information** and **energy advice**[2]. Consumption information is any data relating to energy a consumer has used, possibly with appliance-specific breakdowns, or what a consumer is projected to use (or spend money using) in future based on past usage. Energy advice consists of recommendations for how a consumer could make behavioural changes (how energy is used) or material changes (investing in different appliances or in building modifications, such as cavity wall insulation). We are interested in both types of feedback for the purpose of reducing energy consumption overall, reducing energy consumption at peak times, or increasing comfort for the consumer.

Fischer [1] describes the theory behind how feedback can change consumer behaviour. In short, to change behaviour routine habits need to be broken up, which can happen when consumers become aware of a problem, and recognise both the contribution of and the

[1] SERL was formerly known as the Smart Meter Research Portal (SMRP). Project details can be found at www.serl.ac.uk or https://www.ucl.ac.uk/bartlett/energy/research/research-projects/smart-energy-research-lab-serl

[2] Some sources consider feedback to be equivalent to consumption information, and advice to be separate.

possibility to change their actions. Feedback about what energy is being used can highlight the impact of energy consumption behaviour on a consumer's bills, wasted energy, or the environment, for example. Advice can give consumers a 'sense of control', which in this case would be the means to change their behaviour or building/appliance efficiency. Alternatively, it could be that feedback mainly serves to reduce demand by acting as a "reminder and a motivator, rather than an educational aid", as suggested by the research in Ireland by Carroll *et al.* [2].

As noted by many (for example [3]–[5]), energy, unlike other domestic resources such as petrol in a car or food in the fridge, is far less tangible, and both consumption and waste are less obvious to the consumer. It is generally agreed that the right information, delivered in the right way, at the right time(s) will help consumers reduce their energy consumption (or at least, consume in a more efficient way, which may lead to greater consumption among those who were previously unable to afford the energy they need). The challenge is to establish what feedback should be provided, how, and when to each consumer, which may require careful consideration of many aspects of their lifestyle, home, background, or household.

As noted by Hazas *et al.* "the earliest feedback studies were in the mid-1970s and ranged from feedback on monthly bills, to daily handwritten feedback on a 3 × 5-inch index card placed in each household's mailbox, to real-time feedback on an in-home monitoring device" [3]. With the advent of smart metering and in-home displays (IHDs) in recent years, the potential to provide far greater direct (real-time, in-home) feedback and more detailed indirect feedback (information after processing) has increased dramatically. There have been multiple small-scale trials and several large trials to examine the effects of providing consumers with consumption information and/or advice about their energy use. Results have been mixed, not always quantifiable, and in some cases shown to be country-dependent.

This review sets out to summarise the main findings of the key studies in this area in recent years, and in some cases further back when relevant. Data analysis techniques and algorithms for analysing smart meter data to provide feedback is beyond the scope of the review, and will be the subject of a second report.

Preliminary recommendations for an energy advice service

Recommendations for an effective feedback service

- Deliver feedback via (a choice of) multiple formats, primarily through an interactive website or app, with emails or alerts. However, certain groups of people are less likely to choose to or be able to interact with this type of technology, and alternatives may be required to prevent sample bias and to reach more consumers.
- Deliver consumption information as close to real time as possible, and allow a choice of summary periods, such as daily, weekly, monthly, and annually[3].
- Do not underestimate the importance of the visual design of any type of feedback. See the section on visual design for a range of recommendations.
- Provide a choice of metrics to describe energy consumption. Cost is likely to be most desired, along with energy usage relative to historic use or peer group use. CO_2 equivalent emissions and kWh should also be offered.

[3] Note that this is less important for certain types of intervention, such as those that do not focus on encouraging energy consumption monitoring.

- Show energy usage breakdown by appliance or activity with a pie chart. This may be achieved using additional monitoring equipment or non-intrusive load monitoring (NILM) algorithms [6]. Alternatively, teach consumers how to estimate energy use by appliance with their in-home display, although this may be difficult for some people.
- Encourage consumers to set energy-saving goals, providing information about what is possible for each household individually, and communicating simply and clearly whether the household is on track to meet their target.
- Engage as much as possible with the whole household, rather than just one member, as is often the case [7].
- Advice should sound simple, actionable and be as time/room/event-specific as possible.
- Tailor advice as much as possible to the needs, priorities, resources and motivations of each household.
- Identify vulnerable and fuel-poor consumers and frame advice around increasing comfort rather than saving money or reducing energy use.
- For non-vulnerable/fuel poor consumers, frame messaging in terms of the threat of loss rather than the potential gain/savings, as this has been shown to be a more effective motivator.
- Adapt the feedback programme over time, adding services to grow alongside participant knowledge and to keep people engaged. Target learning, as this has been shown [8] to be the cause of savings rather than, for example, increased engagement with an IHD *per se.*
- Be aware of the power of the media to sway public perceptions of feedback schemes since "media response to a program will decide to a certain extent customer acceptance and engagement" [4].
- Public perception of the messenger can have a large impact on trust in the study, therefore project partners and affiliates should be carefully chosen.

Recommendations for a high-quality study

- The following "minimum recommended set of controls" from Delmas *et al.* [9] should be included for studies:
    - A monitored control group receiving no treatment
    - "Weather controls" – by hour or day
    - "Demographic and household level controls"
    - "Randomization (or pseudo-randomization for opt-in studies)".
- Establish robust methods for quantifying the impact of the feedback or types of feedback (this has not always been the case for feedback studies).
- For a representative sample of the population, consider inviting disproportionately more participants from groups with historically low participation levels, such as households with low income, low energy use, or low education, tenants and multiple-occupant households [10], [11]. Different advertising campaigns may also be needed in order to attract different participants [4].
- Use a large sample, as small samples are shown to have unreliable results [4] and "when within-group variances are large, a large sample size is needed to increase statistical power" [11].
- Conduct the study for a significant duration, ideally at least one year, as short studies have been shown to have highly unreliable results [4], [5], [9], [12].

Acronyms in the literature

AMI	advanced metering infrastructure (2-way communications in metering network)
CF	collaborative filtering
ECF	electricity consumption feedback
HCI	human-computer interaction
HEMS	home energy management systems
IHD	in-home display
ML	machine learning
NILM	non-intrusive appliance load monitoring
SES	smart energy solution
TOU	time-of-use (tariff)

Contents

The potential savings from energy feedback

Quantification

Comparing the effectiveness of feedback approaches across studies was a challenge for the different review papers considered. According to Fischer, "not all studies discuss actual savings; but those who do generally find savings ranging from 1.1% to over 20%. Usual savings are between 5 and 12%" [1]. Schleich *et al.* [13] found 5.5% savings on weekdays and 5.1% savings on weekend days (on average) when feedback was provided alongside IHDs in Austria. In Darby's review, she finds 5-15% savings from direct feedback (display or meter), and "0-10% savings from indirect feedback (processed before reaching user, usually via billing)". The meta-analysis by Delmas *et al.*in 2013 reports that feedback reduced energy consumption on average by 7.4%, but that the savings were only around 2% in those studies with the greatest rigor, including use of a control group and weather and demographics controls [9]. Therefore, we should be cautious about the potential for savings based on the most optimistic study results. Some studies, such as [7], are unable to quantify the response to feedback. In [14] the "goal […] was to capture perceptions of households in relation to their use of the in-home energy feedback display, rather than measure and quantify the level of actual behavioural change". The authors observe "no relationship between the frequency of interaction with the in-home feedback display and the total energy use or net-delivered energy… with some households who indicated daily interaction included amongst the highest and lowest for energy use". Yet 14 out of the 25 households surveyed "believed that they have modified their behaviour due to their interaction with the feedback system". Clearly there is a research gap in terms of hard evidence of effective feedback approaches.

Reliability

Study duration is found to make a difference to the final results, with shorter studies (less than 3 or 4 months) tending to inflate the benefits of the feedback trial [4], [5], [9], [12]. A decrease in interest in feedback over time among some consumers has been observed. For example, in [14], 8/25 households used their display less after 12 months, 3 used it more, and 10 reported no change. Fischer found "no clear indication that long-term projects provide higher (initial) savings than short-term ones" [1], but proposed that "it seems sensible to assume that long-term projects can contribute to habit formation and can therefore engender more persistent savings". The effects are unclear, however, as householders may revert to old habits or the new habits can become a normal part of daily life that no longer require conscious thought [13]. In their meta-analysis, Delmas *et al*. [9] find that around 60% of their sample of field studies lasted for 3 months or fewer, and that overall "for each additional month of treatment, there is a small, but significant increase in energy usage" [9].

Stromback *et al.* [4] find that IHD pilots with fewer than 100 participants show greater energy conservation (on average 11% compared with 5%), and therefore, too few participants may be inconclusive. However, often larger pilots focus on only one type of feedback, so the results may not just be down to the numbers. The authors observe a different trend with informative billing and peak clipping time-of-use (TOU) trials, noting that "feedback pilots seemed to be adversely effected by a large sample size while pricing pilots were not" [4].

The importance of a credible, trusted feedback messenger

Several references (such as [15]–[18]) touch upon the importance of the reputation of whoever delivers the feedback to consumers. The messenger is deemed to be a strong influencer over how the information is received. For example, according to Roberts *et al.* " 'typical energy consumers … exhibit a high level of cynicism about the motives of energy suppliers to promote energy saving and generally low levels of trust in their advice" [17]. Therefore, ensuring that participants in an energy feedback scheme have a clear understanding of who is behind the feedback and how they are different from an energy supplier (if applicable) is important for improving the chances of a positive reaction to feedback. Any choice of messenger must be considered with care.

Delivery channel

There are multiple options for the medium/channel via which feedback is provided. Given the recent development of smart meters and in-home displays (IHDs), many recent studies focus on their use, sometimes in conjunction with other modern developments (websites, emails, texts, applications), or more traditional channels such as bills and other hard-copy materials. In her review, Fischer identifies the most effective feedback choices (those trials in her "best case" group), noting that "all designs that used an interactive element that engages households – through computerized feedback or through required activities like self-feedback or self-meter reading – made it to the "best case" group" [1]. This was also true of trials with computerized feedback "offering multiple feedback options at the user's choice". In general, it is not always easy to compare the effectiveness of different media, as few studies offer feedback via more than one channel, and so reviews such as Fischer's are helpful for comparison. In this section we describe evidence for, and factors contributing to the effectiveness of different media choices for feedback provision.

In-home displays

In-home displays (IHDs) offer a huge advantage for the provision of immediate, interactive feedback to consumers. The review by Faruqui *et al.* [19] found energy savings of around 7% on average across the 12 studies considered. In [4] Stromback *et al.* found that feedback via IHDs "resulted in the highest energy savings", although webpage and informative billing were almost as effective. Locating the IHD somewhere obvious is found to make a big difference to user behaviour, and the look of the monitor can impact consumers' willingness to keep the IHD on show [7]. Many papers highlight the importance of "clear, transparent and flexible" information [7], and in some trials participants complained about the legibility or clarity of information. For example, in [14], 14 out of the 25 households surveyed complained about the legibility or clarity of data displayed numerically or graphically on their IHD. One review [4] found that "64% of the IHD pilots used a combination of 2-3 different forms of feedback information" and that "in only 12% of the cases, one type of feedback was offered (up-to-date consumption)."

The 2017 Smart Meter Customer Experience Study by the UK Department for Business, Energy & Industrial Strategy (BEIS) [20] asked respondents about their interactions with their IHD and perceived impact on their energy consumption. The study found that one year after installation, 45% of respondents looked at information about their energy

consumption on their IHD at least weakly (down from 67% initially) and 59% of people looked at least monthly (down from 77%). Around 29% of respondents still looked at their IHD most days[4]. Respondents were more likely to interact regularly with their IHD if they'd been given information about it at installation, shown how it worked, or asked questions about their energy usage. Almost half of respondents "said their smart meter had helped improve their understanding of their energy consumption over the year". 62% of respondents "felt that having a smart meter had made a difference to how they use energy in their home", although only "around two in ten respondents perceived a decrease in their household energy consumption over the year" [20]. Viewing the first screen or traffic lights was most popular, particularly in the long ter.

Participant engagement with their IHD is considered to be key in feedback effectiveness. Burchell *et al.* suggest a possible "33%/66% split between more and less engaged project participants" [21]. Of the (approximately) 300 households with an Owl monitor installed, "50 were highly engaged with real-time monitoring and on-line historical feedback… 50 were engaged with [the IHD] but did not submit readings or view the on-line feedback" [21]. Berry *et al.* [14] report that in their study displays were mostly used for checking solar PV output and usage, and for monitoring and finding faults with equipment. Only 5 out of the 25 participants reported using the gas information. It is considered that additional measures to improve consumer understanding of and engagement with IHDs will be important for their success as feedback tools [15].

Informative billing and hard-copy materials

Providing information accompanying or directly on a bill, or more generally in hard-copy format receives mixed reviews in the literature. Informative billing can form a long-term approach, which develops energy saving habits over time [1]. The Californian residential study by Martinez and Geltz apparently[5] found that two-thirds of the 400 participants chose paper-based mail as their preferred medium for feedback. The authors of [15] recommend "concise factsheets, limited to key messages" that "incorporate evidence-based design techniques to emphasize [them], such as the use of bright colours, and images tailored to the specific topic of energy efficiency advice". They warn against "generic, non-relevant images" which they found could be "off putting for customers and dismissed as a marketing gimmick".

However, there are also drawbacks associated with hard-copy media. For example, customers can perceive hard-copy materials as wasteful [17], [22]. The focus group in [17] revealed that "typical energy consumers" check their bills but ignore "bill stuffers" and newsletters, sometimes opening bills over the bin to instantly discard the extra papers. Therefore, any feedback would need to stand out on the same piece of paper as the bill. There was also a lack of trust in the energy suppliers providing the bills, although some interest was expressed in an annual energy report. In Fischer's review [1] only one of the projects given in the group of highest scorers for effectiveness was an informative billing project (by Wilhite and Ling in 1995), and overall savings for billing projects ranged from 0-12%[6].

[4] Note that some of the respondents were pre-payment customers who used the IHD to check their meter was in credit.
[5] This study was reported on by Vine *et al.* [31], but we were unable to access the study to verify the report.
[6] Only one project had 0% savings.

Emails, SMS and alerts

Daily emails or SMS were trialled over one year in Denmark by Gleerup *et al.* [10]. Of the 1452 households invited to participate in the trial, 30% accepted the invitation, and the majority of those preferred email-only feedback. The participants in the experimental groups were given one of three types of feedback[7]: 1) daily, weekly or monthly, 2) feedback if consumption this period "deviates with a certain percentage from consumption in the previous period", or 3) feedback sent if consumption is "among the highest or lowest levels of consumption recorded in previous periods". Type three was the most successful in reducing energy consumption, with an average reduction of 3%. The authors suggest that this effect could be stronger in other countries as Denmark has the highest marginal electricity price in the world, and are therefore likely to already be relatively efficient with their electricity use.

More recently, Burchell *et al.* [21] conducted a 'community action' project to reduce energy consumption. A variety of initiatives were involved, such as weekly emails on 'Metering Monday', with specific energy-saving action ideas. The emails were sent to request participants enter meter readings on the website, with the incentive of being entered into a weekly £20 prize draw. The emails had a community feel with strap lines such as 'working together to save energy' and 'don't forget to tell your neighbours', along with references to community events and to what other participants were doing. The scheme also included a web forum and online advice, free energy-saving materials, an eco-gadget library at the local library, and energy activities at a primary school in multiple types of lesson. The impact of the emails must be seen within the context of the many aspects of the scheme, and it is hard to separate their impact from that of the other initiatives. "Importantly, this package of activities was presented and implemented in a style that conveyed the local, friendly, supportive, non-commercial and professional nature of the project" [21]. The authors recommend the use of apps in future feedback initiatives.

Websites and applications

Websites and apps (applications) are easily accessible to most people, although they do require people to seek the information (rather than receiving it in the post, for example). In [14], "13/25 expressed interest in having feedback information available via Wi-Fi or Bluetooth compatibility to other devices such as mobile phones, tablet or laptop computers, with several suggesting some value accessing data when residents are away from home". Burchell *et al.* [21] recommend using apps as good options for tailoring advice, and note that apps are generally very popular. Apps "have the potential to send alerts, notifications and other communications, and to develop a social environment within and between households" [21].

A trial in Germany [23] provided a detailed website with energy feedback and advice, a goal-setting service including feedback on goal achievement, positive reinforcement both "verbally and with the presentation of a smiley", general energy saving tips, and a pie chart with disaggregation from a similar home. An email was sent out at the beginning of each month to let participants know that the monthly consumption data had been updated. The results are yet to be published. Benders *et al.* [24] trialled a website in the Netherlands with 137 intervention participants. They achieved a reduction in energy use of around 8.5% compared to a control group (with 53 participants). Participants were surveyed about

[7] The three experimental groups were given different amounts of choice about the frequency of feedback and the type. There were also two control groups.

their appliances to personalise the advice they received. The previous annual bill was used to determine energy requirements, and surveys were used to estimate how much energy was saved based on reported behavioural or investment change. A similar Dutch trial by Abrahamse *et al.* [11] providing personalised feedback on reported behaviours, 5% reduction targets and tailored advice achieved a reduction in domestic energy and fuel use of 8.3% compared to a 0.4% increase by the control group. However, websites have not been universally successful for energy demand reduction. A smart meter trial in Ulster also set up a website for customers to view consumption by day, week, or month. It contained a news section and children's resource section. However, "none of [the] customers ever visited the website" [25].

Frequency and timing

In general, the most frequent and immediate feedback is deemed to be most useful [1], [5] (although this may change with new types of feedback). As Fischer notes in her review "three of the four designs that give feedback very often (daily or more) are in the "best case" group", while "none of the "less than monthly" […] projects are among the best performing" [1]. Feedback is not offered at such high frequency in all studies, but typically the most frequent option is preferred. For example, in [26] almost two thirds of the participants said they would prefer to have feedback every 60 days, accompanying their bill, and the remaining third preferred it once per year. Raw and Littleford [18] discuss the importance of promoting advice at the right time for a household, such as just after a house move, the arrival of a new baby, or before an extension or refurbishment.

Visual design

In the words of Bartram [27], "The design of effective and motivating personal visualizations is key to improving residential energy use feedback". Fischer's review devotes a section to feedback design. In 2008 she found that, unfortunately, "very few studies have considered the relevance of graphic design or formulation of text", and that "the only two comparative studies show convincingly that households' reactions to graphical designs depend very much on the exact choice of diagram or chart type, labels, scale, symbols, and wording of the explanation. Designs may range from the completely unintelligible to the highly motivating". Fischer also finds that households prefer feedback based on actual consumption in a given period, and clear labelling and explanation of labels, acronyms and technical terms. Components of price need to be explained, and graphics clearly labelled. Pie charts may be preferred for disaggregation, vertical bar charts for historic comparison, and horizontal bars or lines ranging from lowest to highest consumption with the household point on the line [1].

More recently, a lab-based experiment with 43 participants (mostly students) tested three types of design for feedback, and tested which led to the greatest understanding of individual appliance use of energy [28]. The study found that the visualisation with disaggregated appliance use per typical use cycle was significantly better than simple line graphs of aggregated or disaggregated energy use.

Different nationalities show different preferences for graphical designs. In European countries pictorial representations of numbers (rather than graphs) are considered "gimmicky" and "distracting" [17]. Over-use of images can be a problem, as irrelevant

images can be a distraction from the important parts of the text [29]. Fischer writes that "one unanimous finding is that households in all countries approve feedback that is more detailed and more closely linked to consumption actions. It gives them a sense of control and, if delivered with the bill, of being valued and well informed by their utility" [1].

Metrics

There are several options for conveying the amount of energy used. Energy in kWh, power in W, cost (instant or cumulative), and CO_2 emissions equivalent are common choices. Sometimes the user can choose which metric they prefer, particularly if their feedback is delivered via IHD. There is no clear winner from the results surveyed, and, as noted in [1], it can be hard to compare the options, "as almost all projects combine consumption and cost information". In [14] energy consumption and associated greenhouse gas emissions were provided, but there was a desire among participants to match usage with monetary cost. In 1994 Kempton and Layne [30] found that cost was seen as far more relevant than energy (kWh), although, over time, energy is more reliable for comparison. Vine *et al.* [31] did not find strong evidence in their review for any benefits of using environmental metrics. The 2017 study of UK households [20] found that the traffic light display on the IHD was popular for viewing whether consumption was low, medium or high (46% of respondents had used it in the past few months one year after installation). In contrast this study found that only 11% of respondents had looked at the amount of carbon emitted using their IHD. For those who reported using the IHD to go beyond the traffic light display, the majority preferred to review their energy consumption in terms of cost rather than in kWh.

Costs are a common preference among consumers, but they bring their own set of issues, as monthly or daily estimates based on instantaneous use can be excessively high or low due to poor extrapolation techniques [7]. In their review [31], Vine *et al.* find mixed results for the effectiveness of using cost-based feedback. Delmas *et al.* [9] find that energy usage increased when participants were informed about monetary savings or incentives, possibly because the savings were too small, or because they felt entitled to benefit from energy because they were paying for it. In contrast, in Northern Ireland, the introduction of an IHD for pre-payment customers with information including the amount of money left on the meter, the estimated time until the money ran out, and energy usage was associated with a 11-17% reduction in energy consumption compared with other customers [32]. The authors of [4] note that "less than 7% of informative billing samples offered cost (bill) as a form of feedback. However, [the] informative billing samples that [did,] alongside other forms of feedback, produced the highest results". Given the range of options and preferences, effective price extrapolation methods and a range of metrics to suit different consumers could be a sensible feedback choice, possibly with the option of tailoring certain metrics to specific customers based on their motivation for energy reduction.

Disaggregation

Feedback that disaggregates energy use by appliances and by time period has been very popular with consumers across multiple studies. For example, in [14] some households had appliance-level monitoring, while most did not. The households without detailed monitoring were reportedly frustrated that they received no disaggregation. In Fischer's review, "all designs that provide detailed, appliance-specific breakdown are "best cases"", although she notes that "reliable data for the effectiveness of appliance-specific

breakdown… is hard to find" [1]. The review by Ehrhardt-Martinez *et al.* finds the mean and median energy savings from disaggregate real-time feedback to be 13.7% and 14.0% respectively, compared with 8.6% and 6.9% respectively for aggregate real-time feedback[8]. Ueno *et al.* conducted two small studies in Japan monitoring energy usage and providing feedback with a website. In their 2005 study [33], 17.8% savings were achieved with disaggregated monitoring, compared with 9% savings with monitoring without disaggregation in 2006 [34]. These savings are very high, and should be considered with caution due to the very few (order of 10) households in each study. The participants in [7] expressed interest in finding out "how 'greedy' particular domestic appliances were", and better information for appliance purchase choices[9]. However, such detailed levels of information were also identified as a "potential source of anxiety". One responder became painfully aware of the price of having the boiler on, for example.

An alternative to purchasing consumer access devices (CADs) is to use a non-intrusive load monitoring (NILM) algorithm. Kelly's PhD thesis [6] (and related papers) evaluates the benefits of energy disaggregation for reducing energy consumption, and contributes to the tools and algorithms available for inferring energy usage by each appliance, including an open source toolkit for NILM. Kelly finds from a systematic literature review that the absence of comparison within studies between fine-grained disaggregation (each appliance at a high-temporal resolution) and course-grained disaggregation makes it impossible to say which is more effective. His review of the literature comparing aggregate and disaggregate feedback is inconclusive, as two of the four studies are computer simulations, and the remaining two compare aggregated feedback via IHD with disaggregated feedback via a website (with no IHD). The aggregate feedback achieved greater energy reductions, but this is likely to be due to the frequent interactions with the IHD rather than the lack of disaggregated information.

Whilst many studies are unable to disaggregate (or estimate disaggregation through data analysis) down to individual appliances, other papers argue that energy feedback needs to go beyond appliance-specific information to be effective. For example, Stankovic *et al.* [35] propose an algorithm to link appliance use (inferred from NILM) with domestic activities, so that feedback can be framed in terms of the activities people perform in the home – cooking, washing, or listening to music, for example. The authors argue that "providing information on energy use through the lens of activities should resonate more clearly with households", and that "activities are a more stable constituent of domestic life" compared with appliances which come and go [35].

It should be noted that while disaggregated information is clearly popular with consumers, there is an argument that the benefits may not outweigh the costs. The study by Krishnamurti *et al.* [36] found no evidence that participants in a computer simulation study had a better understanding of appliance energy use and monthly cost when provided with disaggregated feedback. The authors suggest that this might be down to 'information overload'. However, the participants only viewed a simulated IHD once (for as long as they wanted, which was typically around half an hour). Perhaps repeated feedback would lead to different results. A different computer simulation study by Herrmann *et al.* [28] found that disaggregation can be very useful for educating consumers about the energy use of appliances, but that the choice of visualisation for conveying the information plays an important role, as discussed above. The authors found that "disaggregation alone did not yield significantly better results: only disaggregation in combination with a simplified visualization that facilitated comparisons between activities resulted in significant learning advantages" [28].

[8] These figures come from 5 disaggregate studies and 23 aggregate studies.
[9] For example, how to compare two kettles when one consumes more power but takes less time to boil water.

Comparisons

In addition to absolute measures of energy consumption, provision of context is useful for consumers to better understand their energy usage. There are two main types of comparison used for feedback trials; *historic* and *normative*.

Historic feedback is the comparison of a household's energy usage with their usage over the same period in the preceding year or month. That is to say, historic feedback compares a household's use with their *own* use in the past. Studies using historic feedback include [4], [7], [14]. Normative feedback compares a household's energy use with that of other households, such as in [1], [21], [26]. The feedback provider typically tries to group households so that fair comparisons can be made between similar numbers of people per house, similar building type, or simply between neighbours. Normative studies have varying popularity across different countries. In the UK, consumers generally show (often strong) opposition to normative comparisons, in contrast with the Finnish and the Japanese [1].

An example of a normative feedback study is that by Burchell *et al.* [21] which provided an online option to see three coloured bars on a chart showing the household's usage, average usage of all participants, and the average of the 20% with the lowest usage, which they referred to as the 'best'. Participants were also able to view feedback relative to the number of people living in their home and relative to the size of their house. In a UK focus group offering historic and normative comparisons [17], "participants expressed strong dislike for any feedback concept which compared their energy use with average, other homes like theirs or other homes in their neighbourhood", and an "overwhelming preference for simple comparison of historical data". A randomized control trial by Schultz *et al.* [37] compared the effectiveness of IHDs with different types of information over a two-week intervention period. The authors found that displaying energy use in terms of cost or energy consumption had a negligible effect on energy use, whereas a basic normative display (traffic lights to indicate energy use relative to similar homes) did reduce energy usage, by 9% and 7% in weeks 1 and 2 respectively, relative to the control group. However, consumers reported preferring the other IHDs, and were more likely to return their normative IHD at the end of the trial. Therefore, merely considering what consumers say they prefer and find most useful may not lead to the most effective feedback approach.

Another issue with normative comparison is the potential for low users to increase their consumption, as their relatively excellent use causes them to relax about their consumption. As Fischer writes in her review, "none of the twelve studies dealing with normative comparison could demonstrate an effect on consumption so far… while it stimulates high users to conserve, it suggests [to] low users that things are going not so bad and they may upgrade a little. These effects probably tend to cancel out each other" [1]. The main consideration before the implementation of normative feedback is the identification of vulnerable consumers who may need to use more energy than average [15].

The argument that efficient households may increase consumption may also be relevant for historical feedback: "it stimulates conservation only when consumption has risen" [1]. A study in Oslo and Helsinki in 1999 [26] found 10% electricity savings (which remained over three years) using a "graphical representation of this versus last year's electricity use (weather corrected) every 60 days". The authors suggest that savings in Norway may be higher than in other countries due to the large amount of electric space heating. Normative feedback was also offered with different presentation styles, and was found to be highly

appreciated. In their 'mass pilot comparison' [4] the authors note that historical comparisons achieved 10.4% energy conservation compared to the 6.8% conservation achieved with other feedback approaches. However, the meta-analysis by Delmas *et al.* [9] found that without "higher involvement interventions (e.g., home energy audits)", neither of these types of comparative feedback "lead to additional energy savings".

Goal setting

An extension of historic comparison is to compare personal energy use with a target or goal, as recommended by multiple papers, such as [11], [38], [39]. The idea is to motivate consumers to reduce their energy consumption by a target amount, and provide feedback on their progress. For example, a German study [23] provided a smiley face on their website if the consumer was meeting their goals, to reinforce the positive behaviour. From a psychology perspective, McCalley and Midden [39] reason that "feedback that does not match an existing goal is of little use". They argue that there is an underlying assumption in energy feedback studies that consumers come to the study with a goal to save energy, but that "this assumption constitutes a fundamental flaw in the energy feedback approach". Their study simulating washing machine operation found that goal-setting was an effective tool for energy demand reduction.

Abrahamse *et al.* [11] introduced a 5% individual reduction target for their experimental groups, and an additional overall (group-wide) 5% target for one of the groups. The authors find no significant difference between the two groups, but the combined package of different types of feedback and goal-setting led to significant savings in direct energy[10]. Anderson and White recommend considering target-setting for a feedback scheme, but question whether the increased complexity involved is worth the benefits, calling for more evidence of the "value of such an option over a longer period of use" [40]. Of the eight IHD features that respondents were asked about for the 2017 Smart Meter Customer Experience Study [20], using the IHD to set a budget target was the least popular (only 9% were using it after one year, down from 10% initially).

Advice

Schleich *et al.* [13] speculate that consumption information alone is insufficient to change householder behaviour in a permanent way, and that the persistent effects observed in their analysis are due to the additional "information and advice on energy-efficiency alongside electricity consumption feedback", which "helped consumers overcome information-related barriers to energy efficiency technology adoption" [13]. Raw and Littlewood write that "the success of advice is… dependent on motive and opportunity being either already present or separately provided" [18].

Content

The authors of the Smart Metering Energy Advice Project [15] make a number of recommendations for the content of effective advice:

- "Messages which break down goals into actions – identifying the what, the where and the how – are likely to prove more effective than generic literacy advice"

[10] *Direct energy* is classed as electricity, gas and fuel for cars.

- Framing advice around daily routine or specific rooms in the house allows customers to identify behaviours that resonate with them and seem less random
- Be clear, simple and specific[11], which may benefit from presenting positive actions as normal and easy to understand
- Be "seasonally relevant and appropriate"
- Prioritise high-impact advice for each household, avoiding irrelevant advice e.g. due to fuel type
- Tailor advice to householder motivation.

Cambridge Architectural Research (CAR) identified the top six behaviours with the greatest overall potential for energy savings (over a year) in their report for the Department of Energy and Climate Change [41]:

1. Turn the thermostat down by 2 degrees (from 20°C to 18°C to save 33 TWh)
2. Turn the thermostat down by 1 degree (from 19°C to 18°C to save 16 TWh)
3. Delay start of heating from October to November (to save 11 TWh)
4. Wear a thick jumper at home in the heating season (to save 6 TWh)
5. Replace standard shower head with a water efficient shower head (using twice per day to save 5 TWh)
6. Use radiator valves to turn off heating in unused rooms (to save 4TWh).

Additional, less impactful, general advice is given in [15]. Vine *et al.* [31] find in their review that in some studies, participants appreciate the energy saving tips in, for example, a customised newsletter; whereas, for example, in a focus group, participants reported that they would automatically discard a generic leaflet. Raw and Littlewood [18] suggest that generic advice (without tailoring to individual households) has "little effect on behaviour", but can become more relevant if combined with other interventions, "resulting in energy savings of up to 5%".

There is a balance to be struck between trialling novel advice with uncertain effectiveness or potential risks, which threatens credibility; and tried and tested advice if it is considered "common sense" or "nothing new" [18].

Consumer motivations

Consumers who change (or desire to change) the amount of energy they consume (or how it is consumed) will be motivated by a variety of drivers. Raw and Littlewood [18] describe a range of motivations, which they refer to as 'consumer needs'. They divide these needs into five categories:

a) **Relating to the wider implications of energy use:** *globally* - climate change, global pollution, depletion of natural resources; *nationally* – energy security, pollution; and *locally* – impact of climate change on sea levels and weather, for example, and local security of energy supply.

b) **Resource-related needs:** *saving money* – on energy bills, or making money through domestic generation, increasing property value; *avoiding waste* – from "an

[11] For example, in [43] Shipworth recommends that advice be very specific about advice actions, not just to generally appliances things off, but, for example, to turn them off at specific times.

inherent dislike of waste"; and *self-sufficiency* – generating own energy or becoming independent of fossil fuels.

c) **Relating to quality of life:** *well-being* – comfort, health, low stress, productive, having safe appliances, security and privacy; *aesthetic appeal* – perception of the look, feel or smell of the home; "*make my life easier*" – greater convenience or reduced time or effort burden; "*confidence in the technology*" – ability to use technology and trust that it will make a difference in the way they want; and *entertainment* – energy needs relating to enjoyable activities such as watching TV or listening to music.

d) **Social needs***: "self-image or recognition*" – identity and "aspirations in a social context"; and *social interaction* – taking care of the needs of other people in the home, socialising within the home, wider social concern for energy technology options for others.

e) **Regulatory needs:** *compliance with legal or industry-based requirements.*

Needs are inter-related and vary over time (throughout the day and in the long term). The authors of [18] recommend identifying "common patterns of need" rather than looking at the "priorities of need". Identifying the key behavioural drivers for a household can be one way of profiling households to tailor advice more effectively.

Tailoring advice for different households

It is generally acknowledged that the more advice can be targeted to a particular consumer, the more likely they will be to respond positively to the advice [1], [4], [15], [16]. The Smart Metering Energy Efficiency Advice Project [15] is a strong advocate of tailoring advice content, style and channel "as much as possible to its target audience". This need for tailored advice is due to the strong role that individual householder choices play in domestic energy consumption. Gram-Hanssen [42] reviews several papers that found that even in identical buildings, heat consumption can vary by a factor of 2 in Sweden and the UK, or by a factor of 3 in Denmark. Electricity consumption (lighting and appliances) can vary by a factor of 5. The most important factors in determining electricity consumption are found to be the number of inhabitants, followed by income[12], followed by the size of the home. More inhabitants use more electricity in total but are generally more efficient per person [42].

Men were found to engage more than women with IHDs in a few studies, such as [7], [14]. In [14], twice as many men interacted with the display as women, although in some cases a woman was the most interested in the household. Studies which involved education in schools found greater participation of women, who may become engaged via interaction with their children. Use of IHDs for school projects was noted by a few authors, such as [7] and [21], and this could be useful for engaging households with children. The authors of [21] felt that the community feel was a strong driver or sense for participants and non-participants in their project, which went beyond schools, involving many local services.

[12] Although Gram-Hanssen suggests that "it could be concluded that these differences in user behaviour could only to a very limited degree be explained by socio-economic descriptions of the inhabitants" [42].

The subject of different consumer motivations is touched upon in multiple papers and reports, such as [4], [15] and references contained therein. Framing and delivering advice differently according to motivation (such as cost saving or environmental benefits) is suggested in [15]. However, it is also noted that care must be taken with advising vulnerable customers about their heating, for example. In [43] Shipworth suggests that feedback should account for attitudes (of all household members) regarding environment and energy saving if actions require little time and money, but that if they require a lot of either then consumers will be more influenced by background factors such as home ownership.

Targeting feedback differently depending on household income is suggested in several papers. For lower income households, [15] recommends "focusing on warmth and fuel/bill savings" while for higher income groups an "environmental slant can be more effective". For low income groups the authors suggest handling messaging around losses with care to "avoid scare-mongering". The authors also highlight that behavioural advice around, for example, thermostat settings, is more likely to engage low income groups; compared with energy efficiency installations and renewable generation options which may be more attractive to higher income households.

Advice to owner occupiers could be different from advice to tenants. In [44] the authors suggest focusing on home renovations and improvements towards owners, and directing behavioural change methods at tenants.

Consumers with low levels of literacy could benefit from advice in multiple formats, using images, videos, verbal advice and in-home demonstration, to avoid over-reliance on written information [15].

Consumers with higher heating needs such as the very young, the elderly and those with certain illnesses or disabilities need to be targeted very carefully. Fuel poor consumers who are already underheating their homes also belong to this group, although they may be less obvious. Targeting measures to improve warmth and comfort without increasing fear of energy bills is important for this group in particular [45]. Age may also be a factor if (one of the less common strategies) gamification is used, as it may not be appropriate for certain age groups [15].

Work by the National Housing Federation found that "Many households had already taken steps to reduce their energy use, limiting the scope for further savings particularly in heating use. For these households, it may be more appropriate to focus on avoiding waste and being smarter about staying comfortable than making outright savings" [45].

Beyond feedback - additional tools and resources

In addition to feedback on how much energy is being consumed and advice for reducing consumption, some projects have provided additional tools or resources. In one pilot scheme [14], 15/25 participants attended a training session on using their IHD, and 7/25 reported that "either more guide material or [more] training would be useful". Stromback *et al.* [4] recommend educating customers alongside informative billing or time of use tariffs to improve energy conservation, but suggest that education lacks impact with IHDs.

Some projects provide objects to complement the IHD or feedback. "Low cost objects, such as magnets or room thermometers, may be used to remind customers of ways to save energy, acting as motivational triggers and stimulating behaviour change" [15]. Pierce and Paulos [46] review multiple energy feedback systems, such as the Power-Aware

cord that lights up according to the amount of electricity flowing through it. Also various "Energy Mementos" such as the "Shake-light bottle" which generates electricity when shaken and can be given as a gift. The goal is to explore "energy as a material that is experienced as a unique and meaningful thing" [46].

So-called 'gamification' – "setting games based around energy efficiency behaviour" [15] may be effective for engaging some consumers, but evidence on the effectiveness, particularly in the long term, is mixed or lacking [15]. Fijnheer and van Oostendorp [47] review and analyse ten energy consumption-related games, and propose a new game based on what they have learned about effective game characteristics for energy consumption reduction. The authors make a number of recommendations for a game that engages the whole family using real-time energy and appliance monitoring.

Challenges for achieving effective feedback

Energy feedback often has to compete with social norms and what Hargreaves [48] refers to as 'practice feedback' – feedback from peers and the media about how tasks should be performed and what is 'normal' or aspirational. For example, leaving appliances on standby, running large baths, or vacuuming highly frequently to retain immaculate carpets. To change habits and preconceptions about normal behaviours would require targeting feedback at specific domestic activities, as well as initiating much wider societal change, by interacting with many actors from marketers to schools and pet shops, town planners and manufacturers [48], [49].

Many papers (for example [1], [4]) recommend providing choice and interactivity for households to increase engagement with feedback. Many trials find that there is one person who is more engaged with feedback than everyone else, and this can lead to arguments about energy use if not everyone is on board with the scheme [7]. Parents often struggle to persuade their children to reduce their use of energy-consuming devices or switch off lights [17]. Engaging children with education at school alongside feedback can be beneficial, and can also lead to more women engaging with energy savings schemes (typically men have been found to be more engaged) [21].

Maintaining engagement can be a challenge, and in [21] disengagement was identified as a problem, as some people became "weary of the feedback, and wanted new forms of feedback that would teach them something new". Striking the balance between high quality, regular, tailored feedback and too much information can be a challenge. Indeed, Roberts *et al.* [17] find that people can become fed up with too much information.

When consumers agree to participate in an energy feedback scheme it is important to manage their expectations around the potential benefits of participation. For example, in [7] the authors report that many people participated to save money, and were disappointed by the actual level of savings because they had such high expectations at the start. In [36] the participants expected that with an IHD they would save around 25$/month (around 25% of their bill), a far higher value than IHD research suggests. At the other end of the spectrum, many consumers have unreasonably low expectations of what is possible. According to [17], 'typical energy consumers' have a "reasonably well-developed understanding of what is involved in saving energy – both in terms of behavioural changes and measures to install – but a firm belief that measures are expensive to install and subject to 'hard sell' tactics". Misconceptions about the price of energy efficient investments result in these types of consumers without any motivation to make changes, as energy consumption is not considered to be "that big a deal" [17].

There can be hidden costs associated with trials that can negatively impact the results. For example, in the Australian study of a new eco-village, highly detailed monitoring took place allowing for high quality feedback [14]. However, the monitoring system consumed a great deal of energy: 38W continuously (3.31MJ per day), around 8% of the net-delivered energy to each home[13]. Therefore, any energy savings from the feedback would have to be substantial in order to overcome the break-even level of 8% and go on to make a noticeable difference.

Even when energy savings occur, they do not always lead to lower consumption in the long run. In the study by Sorrel *et al.* [50], technical improvements of appliances and buildings lead to a reduction in energy use, of which 20% (of the reduction) is lost as consumers prefer the higher comfort they can now more easily afford". There is also the aforementioned issue that can occur when the lowest consumers discover how well they are performing compared to others (or compared to themselves in previous years), and decide to consume more energy.

Research gaps

A number of papers and reports reflect on gaps in the literature or areas lacking sufficient research to draw robust conclusions. In her review [1], Fischer notes a "lack of well-documented large-N studies which could provide reliable data on which kind of feedback will stimulate electricity conservation the most". Stromback *et al.* [4] find this to be particularly pertinent in European pilots, which "tend to be small in comparison to their Australian, Japanese or American counterparts", and recommend "more large pilots, involving between 4000 and 5000 participants" in Europe "to better understand customer segmentation and socioeconomic factors leading to improved marketing messages and program design".

Fischer identifies a "lack of international comparative studies" to capture the potentially "wide cultural and national differences not only in preferences, but also in the kind of information that is effective in stimulating conservation" [1]. Delmas *et al.* discuss the methodological challenges "prevalent in the field", such as small samples, short durations, and no disaggregation [9]. The authors note that " a surprisingly large number of studies do not have control groups or do not take baseline measurements prior to reporting changes in consumption" and that in addition, that many studies do not account for the impact of weather or demographics [9].

Vine *et al.* [31] summarise the following research gaps (in 2013):

- "The effect of feedback on consumers in different demographic groups
- The response effect on energy consumption from different formats of feedback
- Whether feedback continues to work over time or whether it needs to be renewed/reshaped to keep householders engaged and maintain any conservation effects
- The ability for feedback to facilitate the sharing of electricity information between households, friends or neighbours is almost entirely unexplored

[13] Each house had solar panels which would have reduced the net energy delivered, making the monitoring system contributed to a larger percentage of consumption than would have otherwise been the case.

- The scope of design, potential uses and interactions with regard to feedback has been limited
- The divergence of cost-benefit calculations for feedback with advanced metering infrastructure needs to be explored as does the conditions under which the costs of feedback outweigh the benefits."

Additionally, rigorous treatment of questions around the most effective strategies for feedback that have yielded conflicting results in the literature would be of value. For example, determining whether (or under what conditions) pecuniary advice will increase or reduce energy consumption [9], or which households (if any) reduce consumption based on monetary savings advice.

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