Assessing the Value Proposition of Disaggregated Electricity Consumption Data through Real-World Deployments

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ABSTRACT– This thesis examines the role of appliance level electricity consumption feedback for residential demand management especially focusing on households with micro-generation capabilities. A mixed research methods approach involving both quantitative and qualitative methods was developed for investigating the efficacy of such an appliance level electricity use feedback system.
After carrying out an in-depth analysis of all the data instruments it can be concluded that there is no strong and robust evidence that the appliance level electricity use feedback actually helped participants to adopt more sustainable electricity use behaviors for effectively exploiting more from solar PV energy than before the availability of this information. However, it can't be ruled out that the appliance level electricity use feedback has potential to enhance the utility of conventional electricity feedback by creating more awareness among the participants about their energy usage.

1. INTRODUCTION

Residential energy consumption in the European Union (EU) represented 27 % of final energy consumption, or 17 % of gross inland energy consumption, in 2017. The major share of that energy usage in the EU in 2017 came from space heating needs of household (accounting 64 % of final energy consumption in the residential sector). Renewables represented almost one fourth (1/4th) of the households space heating consumption (Courtesy-Eurostat). On the bright side, the installed capacity of renewables is continuously increasing globally especially in Europe (Figure 1). Nevertheless, this rapid growth of renewables has actually increased the complexity and uncertainty for the traditional electricity markets making it harder for them to efficiently balance the supply and demand.

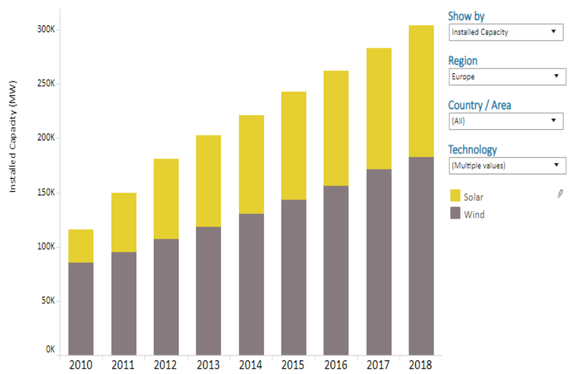

Figure 1. Installed Capacity of Renewables (Solar, Wind)

Traditionally, utilities have focused on the supply side of power generation and never gave too much attention to the demand side of the equation. But the sudden influx of distributed energy generation resources, at the level of the consumer (such as PV panels, storage systems, combined cycle generation systems or wind production systems) has changed the game by making the supply-side very uncertain due to the penetration of fickle natured renewables. That too much variability in the supply side coming from renewables has led to the need of knowing (predicting) much better the demand-side at the local level [1].

Given that residential energy usage makes up a significant portion of the overall final energy consumption in many countries, researchers are keen on understanding the use of advanced information and communications technologies for supporting household in reducing their energy consumption. Some believe that providing household with their electricity consumption feedback may help them reducing their energy consumption. But unfortunately, households haven't received any active information about their energy usage from utilities in the past. They were mostly provided with conventional paper bills with very little information about their electricity use at the end of the month. The electricity bill only included information about the number of units of electricity consumed and how much needs to be paid every month. No information about how many of those total units of electricity were consumed by specific appliances, and which times of the day those specific appliances were used and for how long.

The extensive deployment of smart electricity meters worldwide has made available huge volumes of household electricity consumption data. This data, that is being constantly generated in households worldwide, can be used as a leverage for providing household with near to real-time feedback about their electricity usage to help them better understand their electricity consumption patterns. This way they could make better informed electricity use decisions. In fact, we can only manage what we can understand (in contrast to 'we can only manage what we can measure'). Currently, there are two popular categories of electricity usage feedback: aggregate energy feedback and disaggregated energy feedback (appliance level). Aggregated electricity use feedback might be effective in achieving some electricity use reductions, but it certainly fails to establish a direct and effective connection between the actions and results of household activities. Thus, households are not able to know which of their actions contributed to what percent of electricity consumption and its impact. The only way this connection could be achieved is by providing household information about specific appliances, and times of the day those specific appliances were used [2].

This thesis investigates the role of appliance level electricity use feedback for residential demand management, focusing on households with micro-generation capabilities.

2. LITERATURE REVIEW

In this section, we review the most prominent relevant works with regard to value proposition of appliance level disaggregated electricity use data. Starting by briefly explaining the history of electricity use feedback and its evolution into present day smart and actionable electricity use feedback. Then, we have highlighted works that focus especially on the utility of appliance level disaggregated electricity use feedback for residential demand management.

Electricity Conservation & Feedback

In the past, electricity conservation had never been a priority of utilities as well as consumers. Because conventional business models of utilities allowed them to make profits when more units of electricity were consumed by users, and cheaper electricity prices lured consumers to easily fell prey to this trap. Also, consumers were oblivion of the internalized cost of electricity production from fossil fuels (i.e. Green House Gas emissions - GHGs). However, at present, a vast body of valid and reliable research has concluded that the process of electricity production from fossil fuels releases enormous amount of environment polluting gases (i.e. GHGs), hence, these scientific evidences has helped electricity conservation gaining some momentum and attention around the globe [3].

The problem is that even if consumers are aware of the environmental impact of using excessive electricity and really want to reduce their consumption, often it is very hard to achieve such electricity use reductions. Because electricity conservation cannot be perceived as just one coherent field of action as it is associated with a number of diverse decisions and significant behaviors modifications starting from selecting electricity efficient appliances, and then later their prudent utilization [2]. Therefore, technological changes in buildings and appliances alone cannot ensure electricity conservation. Instead, significant electricity use reductions will only be possible when such technical advancements are combined with sustainable electricity use behaviors of households [4].

When it comes to promoting sustainable electricity use in households, this is no less than a herculean task, given that the invisible, untouchable and abstract nature of electricity. This abstract and invisible nature of electricity makes it hard for householders to establish some emotional involvement hence being unable to take control of their electricity use habits [5].

However, some studies have reported that improved and personalized electricity consumption feedback may help households to develop sustainable electricity use behaviors, eventually optimizing their electricity use [2], [6]–[10]. Therefore, electricity use feedback might not have been imperative in the past, but nowadays, it is believed to be a necessity to drive electricity use reductions especially in the residential demand management [11].

Conventional Electricity Use Feedback

The thing which exacerbates invisible and abstract nature of electricity, is the availability of little or no actionable electricity usage feedback to households [2]. Traditionally, households mostly have been provided with conventional paper bills with very little information about their estimated electricity use, and that too, based on their previous months consumption patterns, rather than accurate electricity consumption and constructive feedback to conserve electricity use [12], [13].

Households usually get the electricity consumption bill on a monthly or in some countries on an annual basis, and it only includes information like how many total units of electricity have been consumed and how much needs to be paid. The electricity bill doesn't convey any information about how high or low electricity is being consumed relative to the average electricity consumption of houses with similar size (which could stimulate a search for reasons), or whether it has increased or decreased (and thus, whether any corrective actions had any effect). No doubt, feedback methods of households' electricity consumption have improved in terms of its cost, and its environmental impacts. But even today, such smart electricity feedback is far from what it could be [11].

Disaggregated Electricity Use Feedback

Conventional aggregated electricity use feedback might be effective in achieving some electricity use reductions, but it certainly fails to establish a direct and effective connection between action and result of households. Thus, households are not able to know which of their actions contributed to what percent of electricity consumption and its impact. The only way this connection could be achieved is by providing household information about specific appliances, and times of the day those specific appliances were used [2].

Since specific appliances and certain activities are linked with households' electricity consumption, the relevance of behavior becomes stronger and clearer. Households could easily detect and understand when provided with appliance level electricity use feedback, the impact of a certain appliance or a certain way of using it and how it affects the total electricity consumption and the money spent. This empowers the consumers by giving them an ability to easily comprehend how altering one behavior or appliance selection could change the endgame [2], [7].

An ideal smart electricity feedback should provide households with information about how, when, or by which appliances electricity was used, giving them better control which may help them with achieving electricity use reductions [13]. Corinna Fischer [11] suggests the following attributes of a successful feedback: increased frequency of feedback, provided for longer time, comparisons with an average of house of similar size, information about environmental impact, real time electricity use, appliance or room- specific breakdown, improved visual design, easy to use medium for presentation of electricity use information.

Methods of Disaggregation

Disaggregation is a technique of converting total electricity consumption of a household or any building into appliance level consumptions. It is possible because every appliance has some unique electric signature which could be separated from the aggregated electricity signal with the help of some sophisticated statistical and machine learning approaches [14].

When it comes to discerning individual appliances signatures from total (aggregate) electricity signal of the whole building, the following are the two prominent approaches: Disaggregation of households' electricity consumption data through direct metering could be done by installing dedicated sensors in the appliances to be monitored (e.g. washing machine, toaster, etc.). There are many sensing solutions capable of doing power disaggregation to acceptable granularity such as Watts up?PRO, Kill-A-Watt, Plug wise [15]. For instance, Kill-A-Watt tell households about the efficiency of appliances connected to it [15]. On the contrary to direct metering sensing solutions, Non-Intrusive Load Monitoring algorithms (NILM) completely eliminate the need for deploying sensor hardware to every appliance, significantly reducing the overall cost of the operation. To do so, NILM algorithms seek to disaggregate specific appliances electricity consumptions from the total electricity consumption of the whole building by using combination of signal processing and machine learning techniques [16].

Value Proposition of Appliance Level Electricity Use Feedback

Appliance level disaggregated electricity use information could have business use cases well beyond the ones highly sought-after (i.e. electricity use reductions via feedback) at the moment by electricity companies. Among the other promising business cases that could monetize or create value out of appliance level disaggregated electricity use information for utilities and consumers are: enhancing utility and customer engagement, promoting ecological behavior, electricity auditing, demand response management and so on [2], [8].

Given that we are interested in exploring the use of appliance level disaggregated electricity feedback for residential demand management, only the field studies which have attempted to test the usefulness of appliance level electricity use feedback for electricity savings are discussed below with elaborate detail. First things first, we wanted to see if smart or appliance level feedback is really needed for triggering electricity use reductions; because maybe conventional aggregated electricity use feedback could be as effective as appliance level electricity use feedback for fostering electricity savings. Therefore, we went through some studies which have compared the effectiveness of both types of electricity use feedback.

According to some studies conventional electricity use feedback (aggregate) could be as effective as appliance level electricity feedback techniques. In some studies, even preferred over appliance level electricity feedback. In fact, there is no strong and robust evidence in published literature that individual appliance consumption information enhances the utility of conventional electricity feedback [6].

For instance, in four controlled field studies that compared appliance level electricity use feedback with aggregated electricity consumption feedback in terms of energy consumption reduction, it was found that in three of them the aggregated electricity use feedback outperformed appliance level electricity use feedback [17] [18] and the fourth study illustrated similar level of performances [19].

A Swedish study [20], [21] conducted with 2,000 households found that subjects who visited a website with aggregated electricity use information decreased their electricity consumption on average around 15% . But this study reported that only 32% of participants visited the website and rest who didn't visit website didn't see any reductions in their electricity. Hence the average decrease in electricity usage across all the households or participants of the study with access to the website was $32\% \times 15\% \approx 5\%$.

One limitation of these studies trying to compare the disaggregated against aggregated electricity use feedback is the fact that they rely on different mediums for presenting disaggregated and aggregated electricity use feedback. For instance, aggregated electricity use feedback was presented using in-home display device (IHD), whereas the appliance level disaggregated electricity use feedback was accessible on a webpage (Bidgely's website). Sokoloski [18] found out in his study that participants provided with aggregated electricity feedback on IHDs were more active than those who were given disaggregated electricity information on Bidgely's website (around 8 times more views were witnessed per day at IHDs than webpages). Other studies also concluded the similar usage patterns and associate this with the lack of households trust on the accuracy and quality of disaggregation [17], [19].

Shahzeen Attari [7] with colleagues performed a randomized controlled trial (RCT) in a New York building apartment for quantifying the usefulness of appliance level disaggregated electricity use feedback for electricity savings and lowering households electricity bills. Ultimately, Shahzeen did report some electricity use reductions while concluding the RCT but disapproved the idea that disaggregated electricity use feedback could be responsible for those electricity savings and associated the smaller reported electricity use reductions with other factors, especially Hawthorne effect.

Another large study [22] [23] was conducted to assess the usefulness of disaggregated electricity use feedback provided by Home Energy Analytics (HEA). The authors report around 6.1% electricity use reductions in electricity saving enthusiasts treatment group, and around 14.5% electricity use reductions for the top-quartile (super electricity enthusiasts).

Two consumer studies [24] conducted by Bidgely, a North American company which uses disaggregated electricity information as a feedback to households for electricity savings, calculated an average of 6.0% domestic electricity use reductions via disaggregated electricity use feedback using robust experimental methodology and sophisticated statistical analysis.

The key issue with the findings reported above is that most of these studies didn't control for the Hawthorne Effect. This is a kind of bias where participants tend to reduce electricity consumption because they are constantly reminded of being part of some electricity reduction study. For instance, Schwartz et al [25] conducted a controlled study with 6,350 participants, where post cards were sent on a weekly basis to participants informing about the study. It turned out that all the participants who received such weekly postcards decreased their electricity usage on average 2.7%. Therefore, the studies which don't control for the Hawthorne effect will tend to over-estimate electricity use reductions attributable to the disaggregated electricity feedback.

Opt-in bias also happens to be something shared by some of the above mentioned field studies ([18], [26]) where participants seek to be the part of the study themselves. Hence, are unlikely to be representative of the general population [8].

As it can be concluded from the above discussed literature, the obtained results are mixed. Some studies reported electricity use reductions via appliance level electricity use feedback while others concluded that appliance level disaggregated electricity use feedback couldn't trigger electricity savings. However, Jack Kelly [8] in his detailed systematic review has examined most of the randomized controlled field studies discussed above; and reported on average around 4.5% domestic electricity use reductions. Furthermore, the author didn't rule out the possibility that disaggregated electricity use feedback could be more effective than conventional electricity feedback.

Ultimately, the idea that disaggregated electricity use information has higher face value than aggregated electricity use information is quite plausible because aggregated electricity use information is unable to help consumers in establishing any connections between electricity consumption and the impact of daily practices, in contrast to disaggregated electricity information. Without disaggregated consumption information, feedback will be less meaningful for householders and cannot trigger sufficient reflection or learning [6].

The other key target group of our interest are prosumers who have the ability to produce electricity for themselves using solar PVs or wind turbines in homes. No doubt, micro-generation democratizes the use of electricity and plays a key role in accelerating the energy transition. But discussing the benefits of micro-generation is beyond the scope of this thesis. For now, we are specifically interested in finding out if appliance level electricity use feedback could help micro-producers to be more self-sufficient by adopting more sustainable electricity use behaviors.

For testing above mentioned hypothesis Jacky Bourgeois [27] selected 18 households/ micro-producers (solar PV owners) for the period of eight months and designed an experiment to find out what actually triggered demand shifting behavior to optimize the consumption from solar PV production. Participants received different interventions; like delayed feedback, real time feedback, proactive suggestions, and contextual control to help them utilize more of the energy produced by their solar PV panels. Jacky concluded that both types of feedback, delayed and real time were not effective for shifting behaviors. On the contrary, proactive suggestions (e.g. suggesting the best time for doing laundry), and contextual control (i.e. simplified app on tablet that could control the washing machine) did show positive results and proved to be effective in promoting sustainable electricity use behaviors.

In another study Meiken [28] concludes that micro-generation could also increase the use of electricity by households mainly for two reasons. First reason is due to the increase sense of comfort and other reason has to do with the feeling of resentment towards electricity companies where households want to consume all the solar PV production not wanting electricity companies to get anything for free.

3. CONTEXT AND SAMPLE SELECTION

This thesis comes under the umbrella of H2020 SMILE Smart IsLands Energy systems[1] project (SMILE), which is currently ongoing in Madeira Island, Portugal. The SMILE project will demonstrate the real-world integration of different smart grid technologies on three different European islands, more concretely Madeira Island in Portugal, Samso in Denmark, and Oarkney's in the United Kingdom.

Against this background, one of the main goals of the SMILE project in Madeira Island is to leverage the potential of technologies like Battery Energy Storage Systems (BESS) and energy efficiency programs such as individual appliance consumption eco-feedback to facilitate the future integration of significant additional solar and other renewables generation in the Madeira Island electric grid.

The local SMILE team recruited participants using different platforms such as online advertisement

[1] H2020 SMILE, https://h2020smile.eu

campaigns, handing over formal letters, contacting people directly on their phones, organizing information sessions about the study in collaboration with local DSO/TSO (EEM) [29]. In the end, six participants (Table 1) were selected to have their eco-feedback systems enhanced with individual appliance consumption information. We have also selected a control group (Table 2) just like any other controlled field trial to account for the influence of unforeseen external events. Our sample have been assigned some coded identity ensuring privacy compliance, hence they would be referred with their coded identity in this document (Table 1, Table 2).

Experimental Group	
Coded Identity	Original Identity
A	UPAC 1
B	UPAC 3
C	UPAC 4
D	UPAC 10
E	UPAC 13
F	UPAC 14

Table 1. List of Participants –Experimental Group

Control Group	
Coded Identity	Original Identity
G	UPAC 2
H	UPAC 5
I	UPAC 6
J	UPAC 9
K	UPAC 11
L	UPAC 12

Table 2. List of Participants –Control Group

Sample Description

When it comes to demographic information, starting from the household size in our sample which ranges from 2 to 5 people, with an average of 3.5 people in one household. If we talk about the age group then we could see that our sample is blended with varied age groups as expected in typical household starting from 7 years old till 64 (average age is 35.57 years old).

When it comes to demographic information, starting from the household size in our sample which ranges from 2 to 6 people, with an average of 3.66 people in one household. If we talk about the age group then we could see that our sample is blended with varied age groups as expected in typical household starting from 5 years old till 84 (average age is 34.90 years old).

The yearly income of majority of our sample was found to be below 40.000 euros. Most of them got higher degree education, and also glancing at their professional occupations showed that they have very diverse professions.

When it comes down to geographical location, most of our participants live along the south coast of Madeira island. This could be explained with following two (2) reasons; the north coast of Madeira got very small population density, and the south coast boasts higher sun incidence [30].

4. RESEARCH METHODOLOGY

There are several research models available for facilitating researchers to develop an effective research methodology for conducting quality research. But when it comes to comprehensiveness and applicability to wide range of research projects, no other models can hold candle to research onion model [31]. Therefore, research onion model was used for developing the effective research methodology to answer our research questions.

The most effective and easiest way of applying research onion model to any research project for developing effective research methodology is working backwards. Starting from the inner most part of the onion (i.e. selection of type of data collection instruments) then that collected data could be further analyzed for either building or testing the hypothesis depending on the pre-defined research approach (i.e. deductive or inductive) and research philosophy (i.e. ontological and epistemological beliefs) of the researcher.

5. DATA COLLECTION INSTRUMENTS

Given that this thesis attempts to examine the role of appliance level electricity consumption feedback for residential demand management especially focusing on household with micro-generation capabilities, thus, a mixed research approach involving both quantitative and qualitative methods was developed for investigating the efficacy of such an appliance level electricity use feedback system.

Quantitative Data Collection Instruments

The following quantitative data collection instruments were used for our study:

- Electricity consumption and solar PV generation data taken from smart-meters installed at the mains.
- Individual consumption of selected appliances taken using plug-level smart-meters.
- Pre and Post intervention survey about individual appliance consumption.

Quantitative Data Collection Instruments

The following qualitative data collection instruments were used for our study:

- Behaviors Questionnaire
- Post Intervention Interview

6. DATA ANALYSIS & DISCUSSION

In this section, an in-depth analysis and discussion of all the data instruments have been carried out to answer our research questions.

Pre and Post intervention survey results

We conducted an online survey, in which we provided our participants with a list of electric appliances, and asked them questions to assess their knowledge about domestic appliances electricity usage.

We conducted this survey twice, one prior to the participants were given appliance level electricity use feedback and one after three months of the availability of appliance level electricity use feedback. The intent was to see if the availability of the appliance level electricity use feedback increased household knowledge about the impact of a certain appliance electricity consumption or a specific way of using those appliances and how it affects the total electricity consumption and the money spent.

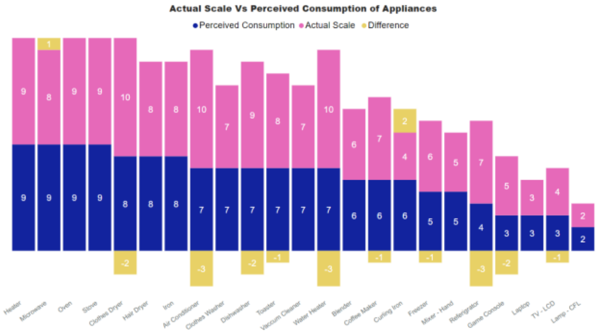

Figure 2. Pre Intervention Survey Results

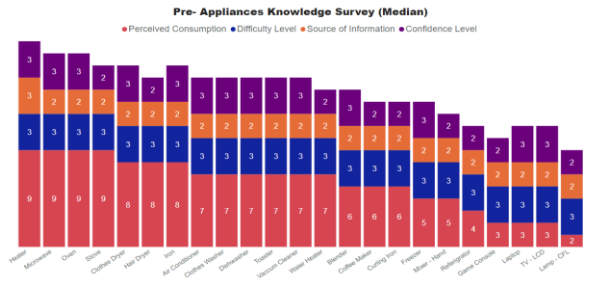

Figure 3. Pre Intervention Survey Results

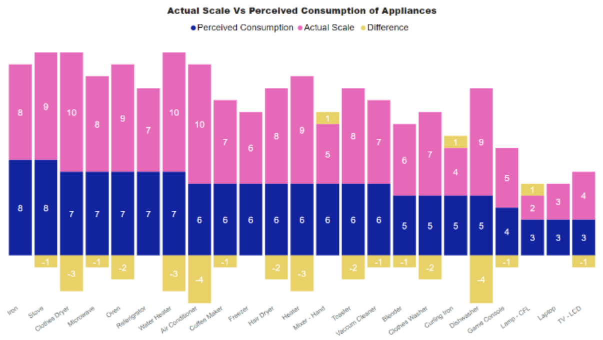

Figure 4. Post Intervention Survey Results

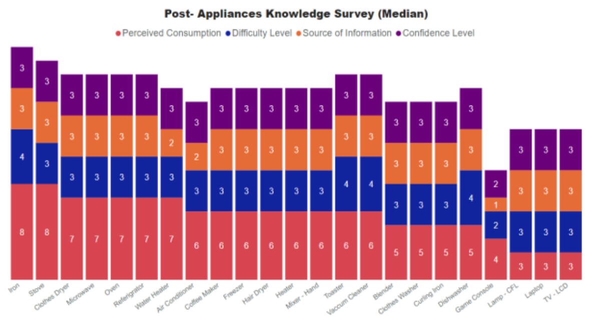

Figure 5. Post Intervention Survey Results

The responses from the both pre and post intervention survey results demonstrate that the majority of the participants tend to under-estimate electricity use of most of electricity intensive appliances.

However, when it comes to measure the level of difficulty, source of information and confidence level of participants in answering the Question 1 about reporting electricity use of appliance. There are some interesting variations. Overall, it looks like that participants found it easy to report consumption of some appliances after the availability of the appliance level feedback reflected in post-intervention survey results. And most of the participants think that they reported consumption of appliances based on their knowledge after the availability of the feedback rather than educated guesses (pre-intervention survey) before the feedback. Confidence level in reporting consumption of appliances has also increased post feedback.

The improvements in reporting consumptions of different appliances in terms of difficulty level, source of information and confidence level could be because of self-reporting bias as it didn't help bridging the gap between perceived consumption and actual consumption of appliances before and after the availability of appliance level electricity use feedback.

Behavior Survey Results

In order to understand the participants perceived easiness, and usefulness of adopting sustainable electricity use behaviors associated with the photovoltaic proliferation.

We gave participants two categories of electricity use behaviors which could lead to photovoltaic proliferation: one category of behaviors represented activities focused on shifting of electricity usage from periods without production to during the day when there is excess solar production. The other category of behaviors focused on replacing electricity intensive activities with alternative sustainable practices like playing board games instead of PlayStation and asked our participants to rank on a Likert-scale from 1 to 5, the perceived easiness and usefulness or uselessness of adopting these two category of behaviors.

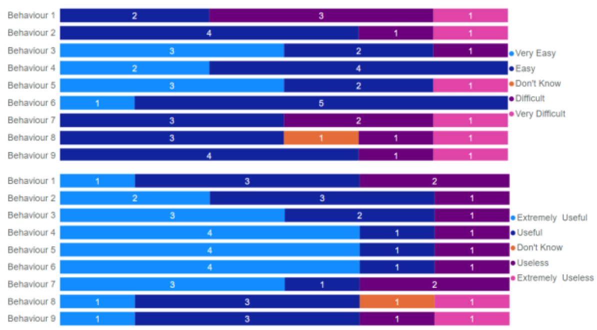

Figure 6. Behavior Survey Results –Shifting Category

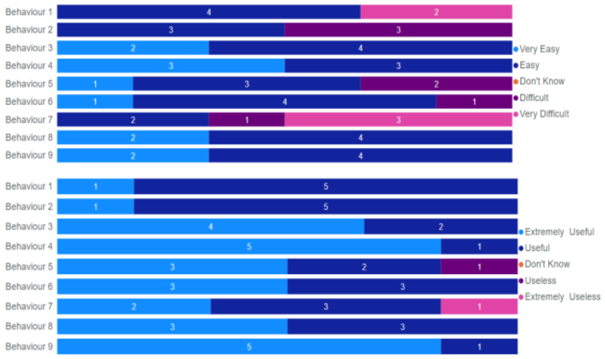

Figure 7. Behavior Survey Results –Replacing Category

The responses from the behavior questionnaire in both categories of sustainable electricity use behaviors (shifting and replacing) clearly demonstrate that the majority of the participants consider most of the behaviors in the shifting as well as replacing category either very easy or easy, and extremely useful or useful to adopt.

However, there have been some interesting observations in both the categories of sustainable electricity use behavior. Let's start with shifting category first (Figure 6), behavior 1 (playing PlayStation during the day instead of night) was perceived difficult to adopt in majority of the responses that could be because only the kids play in our sample. And it's hard to make them stop playing. Especially if they are in the vacation. Also, it's the only time they are home because of school. In the same category, behavior 8 (Turn of freezers during the night to have them on during the day) has got one don't know, and one extremely useless rating maybe that's because participant thinks freezers don't consume a lot of electricity which can be complemented by pre and post knowledge survey results (Figure 2, Figure 4) in which participants have under-estimated the electricity usage of Freezer.

The replacing category has also illustrated some interesting variations. For instance, behavior 2 (preparing less energy intensive meal or with a slow cooker, and behavior 7 (using public transport once a week while the EV is charging) (Figure 7) has shown contrasting results to majority of responses. If we look at behavior 7 and 2, the majority of participants perceive very difficult or difficult in engaging in these behaviors which clearly shows that consumers may be concerned about their electricity bill and actually like to discuss the topic with friends and family. However, this is not such a hot topic that keeps them from following their normal lives, or to monitor their consumption every hour. Thus they are not willing to comprising their comfort over a small saving at the end of the month.

Electricity Consumption Data

Given that appliance level electricity use feedback became accessible to all the participants in our study in June 2019. Thus, the aggregated energy consumption and solar PV production data of participants before and after the availability of the feedback have been used to assess the added value of the appliance level electricity use feedback for household in managing their domestic energy consumption.

The analysis have been made with respect to self-consumption, excess solar PV, and total energy consumption before and after the individual appliance eco-feedback. For the purposes of assessing the contribution of feedback to help participants in enhancing photovoltaic proliferation self-consumption (to measure exploitation of PV production), and excess solar PV has been chosen as a metrics. Both of these metrics can help us clearly distinguish the participants who managed to make use of feedback in effectively exploiting the PV production from the one's who didn't.

Individual analysis about electricity consumption and solar PV generation data of all the participants in the experimental and controls groups have been discussed in details in the main thesis draft and are summarized below. Cutting it short, after conducting interviews with participants of the experimental group and looking at their electricity consumption and solar PV generation data two things became clear: increased awareness due to the availability of the appliance level feedback, and other reason having lack of flexibility (excess solar PV energy).

Firstly, most of the participants who had excess solar PV energy, agreed in the interviews that they are aware of their excess solar PV energy thanks to the accessibility of appliance level electricity use feedback platform, but they have got very strong routines making harder for them to switch to more sustainable electricity use practices to effectively exploit photovoltaic potential.

The other reason for not being able to exploit solar PV energy is that they produce more from their solar installation when they are not home hence can't consume.

Regarding the awareness, they are also more aware of the consumption of individual appliances. E.g., they could not believe that the TV would consume that much. This means that they can take some measures to also reduce consumption. This is what happened with participant F whose individual appliance consumption data reveals a reduction in consumption from the TV and Oven.

Secondly, those who didn't have lot of excess solar PV energy said that they know how to effectively exploit solar PV production but don't have lot of flexibility (excess solar PV energy) and planning to enhance their solar PV capacity. The problem with less or negligible excess solar PV energy is that there is no point to move things around because after all you'll have to get most of the power from the grid. This is even more evident in the cases with time of use tariffs that have a more expensive price during the day. If you have this tariff, you can only shift a load to the afternoon if you are sure that almost all the consumption will be covered by the solar PV. Also, in scenarios when they have very minimum excess energy, self-consumption in not a good measure for accessing the value proposition in the cases that it is already very high.

7. CONCLUSION

In this section, conclusion and future work directions have been presented. Some of the limitations of this work and the lessons learned have also been discussed, and for each limitation one or more lessons learned and how such limitation may be addressed in the future have also been discussed.

Research Implications

If we look back at (Data Analysis and Discussion) chapter in order to assess to what extent our main research question mentioned below has been answered.

Overarching RQ: Does disaggregated electricity consumption feedback offer any added value to household especially in our case micro-producers (photovoltaics owners)?

After carrying out -an in-depth analysis of all the data instruments it can be concluded that there is no strong and robust evidence that our appliance level electricity use feedback actually helped participants to adopt more sustainable electricity use behaviours for effectively exploiting more from solar PV energy than before the availability of appliance level electricity use feedback. However, it can't be ruled out that the appliance level electricity use feedback has potential to enhance the utility of conventional electricity feedback by creating more awareness among the participants about their energy usage.

Most of the participants agreed in the interviews that they are more aware of their overall energy usage, and excess solar PV energy thanks to the accessibility of appliance level electricity use feedback platform. That's the reason some of the participants already deployed solutions (solar PV recovery system – Participant B) to fully exploit the PV potential and others like Participant E are considering deploying solutions like intelligent scheduling solutions to exploit whatever excess solar PV energy they have got. While some participants are willing to take steps due to increased awareness others find themselves completely helpless when it comes to changing their strong unsustainable routines making harder for them to switch to more sustainable electricity use practices to effectively exploit photovoltaic potential. The other reason for not be able to exploit solar PV energy is that they produce more from their solar installation when they are not home hence can't consume. In these cases, battery energy storage systems seem like the only viable solution, still the prices of storage are still far from making this solution appealing for the regular prosumer in Madeira Island.

Ultimately, we believe that prosumers are particular concerned about their electricity bill, mostly due to the investments made in solar PV. Furthermore, even with increased knowledge from individual appliance consumption, the daily routines pose significant challenges to maximize self-consumption.

Limitations and Lessons Learned

Some of the limitations of this work and the lessons learned are discussed below. For each limitation one or more lessons learned and how such limitation may be addressed in the future have also been discussed.

Limited Duration of the study

As this is a master's thesis work, it has a limited timeframe which end up being of on the key limitations of this work, influencing the results of the study. Furthermore, due to the real-world nature of our study, several things were happening during the deployments, including people coming and moving in from the house (holidays, summer season) and the installation of additional appliances and battery energy storage systems. Ultimately, if we had more time then we could have seen whether this increased awareness reported by participants would actually change their energy use decisions or not. But this research would continue even after the submission of this master's thesis.

Engaging whole Family

During most part of our study we've been able to interact with only one or two persons in each household. Normally the person that responsible for accessing the feedback platform, was answering all of our interview questions as well as responding our questionnaire/surveys.

Some participants discussed during interviews that they know about excess solar PV energy thing and has also suggested many times other members of the family about using some less energy use appliances when possible. For instance, one participant said they have an appliance for cooking food which consumes very less energy than stove or microwave but his wife prefers using stove and microwave for cooking. Therefore, we deem that engaging the whole family in the study is indispensable.

Less Engagement with Feedback Platform

One other thing which was commonly reported by all the participants is that in the beginning they were more actively using the feedback platform due to curiosity and novelty effect but then later they were rarely active on the feedback platform. Also, because they say its hard for them to login each single time using laptop/computer. They suggested it would be better if they could access the same information on some mobile that would come handy to them.

FUTURE WORK DIRECTIONS

First things first, if the value of disaggregated electricity consumption feedback platform needs to be investigated for household with micro-production capacities then the participants must have significant excess solar PV energy giving them a possibility to better understand their consumption to fully exploit the excess solar PV energy. Because if participants have not got significant excess solar PV energy then the value proposition of appliance level electricity use feedback for micro-producer diminishes to nearly zero, as there is not much one can talk about the value proposition with respect to self-consumption.

Another important future research direction would be to study the value proposition of disaggregated consumption data in different scenarios combining the solar PV with Battery Energy Storage System (BESS).

So, Ideal future work must have large representative sample, each participant with significant excess solar PV energy if value proposition being tested only for micro-producers. The study must have long duration at least more than a year to capture and offset different externalities of real-world deployments. Study design must engage the whole family in the study for the reasons discussed above in the limitations section. Last but not the least, future feedback platform must be handy to access and should have easier to understand user interface (UI).

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