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

Fayaz Ahmed

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. Duarte Nuno Jardim Nunes

Dr. Amâncio Lucas de Sousa Pereira

Examination Committee

Chairperson: Prof. Duarte de Mesquita e Sousa

Supervisor: Dr. Amâncio Lucas de Sousa Pereira

Member of the Committee: Dr. Catarina Maria da Cunha de Eça Calhau Rolim

November 2019

Acknowledgements

First and Foremost, I would like to thank my family, my friends for their support, patience and understanding throughout my academic years and helping me to be who I am today.

Then, I would like to extend my sincere gratitude to InnoEnergy Master School for sponsoring my MSc programme Clean Fossil and Alternative Fuels Energy (CFAFE). This thesis work has been conducted for the fulfillment of this InnoEnergy double degree MSc CFAFE programme.

I would like to thank my supervisor, Prof. Duarte Nuno Jardim Nunes for the support, guidance, availability and teachings given during the elaboration of this master's thesis.

I would also like to acknowledge the support from Prof. Konrad Świerczek for being my thesis supervisor in AGH UST Poland and help me getting through this process.

Last but not the least, I would like to thank Dr. Lucas Pereira for his cooperation and for the help given during the experimental work, data analysis and writing of the dissertation.

InnoEnergy Knowledge Innovation Community

AGH

TÉCNICO LISBOA

Abstract

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 thesis examines the role of appliance level electricity consumption feedback for residential demand management especially focusing on household with micro-generation capabilities. 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.

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.

Keywords

Energy Feedback, Residential Demand Management, Solar PV, Self-consumption, Value Proposition.

Resumo

A ampla implantação de medidores de eletricidade inteligentes em todo o mundo disponibilizou enormes volumes de dados de consumo de eletricidade doméstica. Esses dados, que estão sendo constantemente gerados em residências em todo o mundo, podem ser usados para alavancar um conjunto de serviços para fornecer às residências feedback quase em tempo real sobre o uso de eletricidade, ajudando-as a entender os seus padrões de consumo de eletricidade.

Esta tese examina o papel do feedback do consumo de eletricidade ao nível dos aparelho individuais para a gestão da demanda residencial, especialmente com foco nas residências com capacidades de microgeração. Uma abordagem de pesquisa mista envolvendo métodos quantitativos e qualitativos foi desenvolvida para investigar a eficácia de um sistema de feedback sobre o uso de eletricidade em nível de aparelho.

Depois de realizar uma análise aprofundada de todos os instrumentos de dados, pode-se concluir que não existe uma evidência forte e robusta de que o nosso feedback sobre o consumo de eletricidade ao nível de equipamentos domésticos realmente ajudou os participantes a adotar comportamentos mais sustentáveis de uso de eletricidade para efetivamente explorar mais a energia solar fotovoltaica do que antes da disponibilidade do feedback sobre o uso de eletricidade em nível de aparelho. No entanto, não pode ser descartado que o feedback do uso de eletricidade de forma desagregada tem potencial para melhorar a utilidade do feedback de eletricidade convencional, criando mais consciência entre os participantes sobre seu uso de energia.

Palavras-chave

Feedback de Energia, Gestão da Procura Residencial, PV Solar, Autoconsumo, Proposta de Valor.

Table of Contents

List of Figures

List of Tables

List of Acronym

BESS	Battery Energy Storage System
SMILE	Smart Island Energy Systems
UPAC	Unit of Production for Self-Consumption
DSM	Demand Side Management
NILM	Non-Intrusive Load Monitoring
EEM	Electricity Company of Madeira
EMS	Energy Management System
DSO	Distribution System Operator
TSO	Transmission System Operator
PV	Photovoltaics
RES	Renewable Energy Systems
KPI	Key Performance Indicators

1 Introduction

1.1 Motivation

In 2015, residential energy consumption in Portugal represented 15.8 % share in the total final energy consumption of Portugal, which is substantially below the EU average (25.4 %) of final energy consumption. The major share of that energy usage in the European Union (EU) came from space heating needs of household (accounting 64 % of final energy consumption in the residential sector), with renewables representing for almost one fourth (1/4th) of European Union (EU) households space heating consumption (Courtesy-Eurostat).

On the bright side, the installed capacity of renewables is continuously increasing globally especially in Europe (Figure 1.1). 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 side.

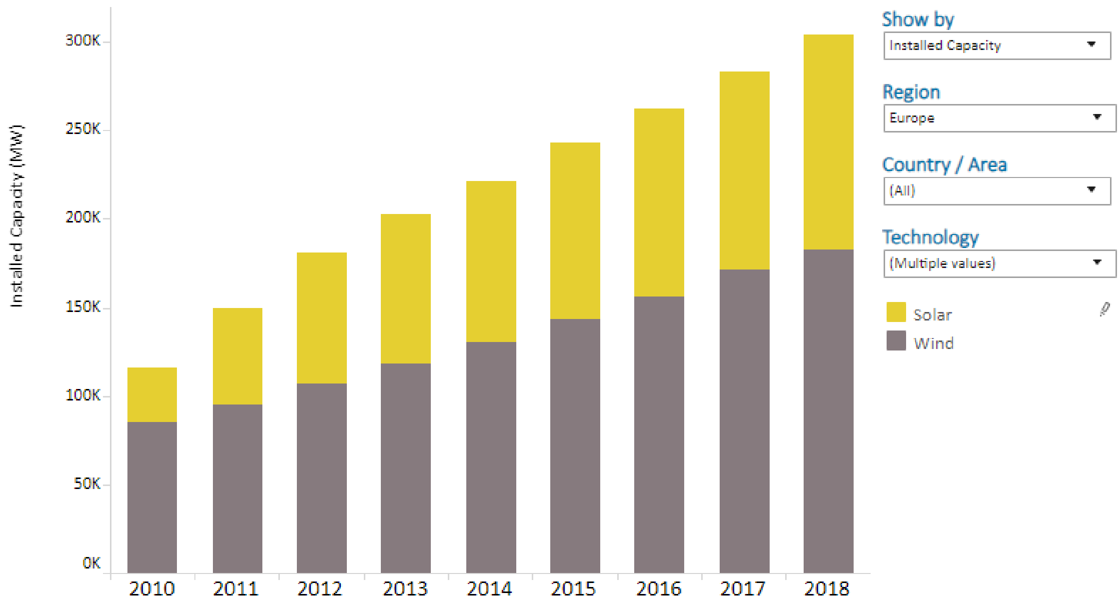

Figure 1.1 Installed Capacity (Courtesy -IRENA)

Traditionally, utilities have always 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 significant portion of overall final energy consumption in many countries, thus researchers are keen on understanding the use of advanced information and communications technologies in supporting household for reducing their energy consumption.

Some believe that providing household with their electricity consumption feedback may help them reducing their energy consumption. Unfortunately, traditionally households haven't received any active information about their energy usage from utilities. 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.

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 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].

This thesis investigates the role of appliance level electricity use feedback for residential demand management.

1.2 Problem Statement

Appliance level electricity use feedback is believed to have potential to empower the household by providing them with information about how altering one behaviour or use of certain appliance could change the overall electricity consumption of the house. But the problem is that there are not enough empirical evidences to prove the value of appliance-wise disaggregation when deployed in the real-world.

This thesis is an attempt to collect empirical evidences through real world deployments in order to assess the real value of appliance level electricity use feedback for household especially with micro-generation capabilities.

1.3 Research Question

This thesis is guided by the overarching research question:

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

There is a sub-set of relevant research questions to investigate how householders interact with and make sense of appliance level electricity information feedback. These questions are listed below.

RQ2: How much household know about their electricity use?

RQ3: Which sustainable electricity use behaviours household think are easy and useful to adopt?

RQ4: What are the common barriers and motivations of engaging in sustainable electricity use practices?

1.4 Thesis Structure

This thesis document consists of six (6) key chapters. Starting with an introduction chapter then subsequently followed by following chapters: theoretical framework, context and sample selection, research methodology, data collection instruments, data analysis and discussion, and last but not the least conclusion and the future work directions. The structure of the thesis is outlined in more detail below:

Chapter 2 covers the most prominent relevant works with regard to value proposition of appliance level disaggregated electricity use data. Starting from briefly explaining the history of electricity use feedback and its evolution into present day smart and actionable electricity use feedback. Then, I have reviewed works that focuses especially on the utility of appliance level disaggregated electricity use feedback for residential demand management. Furthermore, methods of disaggregating appliance specific signatures from aggregated electricity signal of whole building have also been reviewed, along with their advantages and disadvantages. I have concluded this chapter by highlighting research gaps found in the literature and how our study attempts to fill those gaps along with some future research directions.

Chapter 3 presents clear description and scope of the thesis followed by the details about recruitment, selection, and characteristics of our study sample.

Chapter 4 describes all the necessary systematic stages which were chosen for developing the effective research methodology to answer our research questions along with solid explanations and justifications for each level of methodological decisions.

Chapter 5 describes all the details about the different types of data collection instruments which were selected for answering our research question about assessing the utility of appliance level electricity use feedback for micro-producers (photovoltaics owners), along with solid explanations and justifications for selecting those types of data instruments. I have also described about the methods, and tools used for collecting these types of data collection instruments. The details about UI Design of both aggregated and disaggregated electricity use information elicited by our feedback system have also been provided in this chapter.

Chapter 6 presents an in-depth analysis and discussion of all the data instruments to answer our research questions. Including detailed information of the metrics used for our analysis.

Chapter 7 includes the conclusion and future work directions. Some of the limitations of this work and the lessons learned have also been discussed. For each limitation one or more lessons learned and how such limitation may be addressed in the future have also been discussed.

2 Theoretical Framework

In this chapter, I have reviewed the most prominent relevant works with regard to value proposition of appliance level disaggregated electricity use data. I started by briefly explaining the history of electricity use feedback and its evolution into present day smart and actionable electricity use feedback. Then, I have reviewed works that focuses especially on the utility of appliance level disaggregated electricity use feedback for residential demand management. Furthermore, methods of disaggregating appliance specific signatures from aggregated electricity signal of whole building have also been reviewed, along with their advantages and disadvantages. I have concluded this chapter by highlighting research gaps found in the literature and how our study attempts to fill those gaps along with some future research directions.

2.1 Electricity Use Feedback and Electricity Conservation

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 behaviours 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 behaviours 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 behaviours, 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].

2.2 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].

Kempton and Layne [12] equates conventional electricity use feedback techniques to shopping in a grocery store with no price tags on individual items. Imagine if a householder goes for shopping in a grocery store every day for the whole month and buys daily use products (with no price tags) without getting to know their prices and receives a total bill of all the purchases at the end of the month. By doing so, the householder will have no idea about how much it was spent on the shopping unless she gets the total grocery bill at the end of the month. Same goes for electricity, householders don't know how much they have to pay at the time of electricity consumption unless they receive a monthly bill. Electricity is a kind of strange commodity which doesn't let the household experience the effect of "diminishing stock" like other consumer goods making it hard for electricity conservation [11]–[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].

2.3 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].

Given that specific appliances and certain activities are linked with households' electricity consumption, hence the relevance of behaviour 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 behaviour 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.

2.3.1 Benefits of Disaggregated Electricity Use Feedback

Disaggregated electricity use feedback boasts the following key benefits [14]

- Electricity use reductions.

- Detection of malfunction appliances
- Introduction of sustainable behavioural changes
- Channelling electricity auditing programs
- Electricity efficiency and segmentation

2.3.2 Methods of Disaggregating Electricity Use Information

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].

This information then leads to the creation of various added-value services such as energy efficiency measures that can lead to behaviour change or appliance substitution, client segmentation, dimensioning PV solutions, among many others.

When it comes to discerning individual appliances signatures from total (aggregate) electricity signal of the whole building, the following are the two prominent approaches:

2.3.2.1 Disaggregation by Direct Metering (Plug-level Sensors)

Disaggregation of households' electricity consumption data through direct metering is 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].

These direct metering solutions/plugs are deployed at desired power outlets to measure power output of those appliances. When it comes to accuracy and straightforwardness no other technology could disaggregate the electricity use information of households like sensors technology does, because it collects the individual appliance consumption data without requiring any further processing (i.e., statistical analysis or machine learning algorithms). Nevertheless, there are no free lunches, this accuracy comes with a high capital cost and complexity of deployment [16]. Because a typical household has a high number of appliances, deploying sensors to each appliance then the cost of deployment would easily reach up to thousands of dollars and sensors also face severe connectivity problems causing lot of missing data [15]. Therefore, it might be feasible to such use sensors for small-scale studies, but it is certainly unpractical for nationwide rollouts. [6], [17], [18].

2.3.2.2 Disaggregation by Non-Intrusive Load Monitoring Algorithms (NILM)

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 [19].

The base assumption behind NILM algorithms is that given that all the electric appliances exhibit different characteristics during steady-state and transition states (e.g. changes in active and reactive power), it should be possible to discern the appliances responsible for such changes in the aggregated signal by means of sophisticated statistical and machine-learning techniques [20] [16], [19], [21].

Despite NILM being a highly sought-after research topic, it is still far from ready for disaggregating electricity on wide-scale real-world deployments because there is no one exact solution which could be applicable to all the households' appliances. For instance, when the appliances with similar signatures are turned on simultaneously, NILM faces uphill task of figuring out specific appliance unique electric signature from the total electricity use pattern. Furthermore, the performance of existing NILM algorithms tends to deteriorate considerably as the number of appliances to disaggregate increases [15] [16], [21], [22].

Researchers have also tried to come up with hybrid solutions by combining the benefits of NILM and direct metering methods. Intelligent inferencing capability of NILM, and the accuracy of sensors when combined together could definitely increase the accuracy and scalability of such solutions with optimized cost [15].

These and other technical issues are the subject of attention from many researchers worldwide. While an extensive discussion of NILM algorithms is out of the scope of this thesis, the interested reader should refer to a number of literature review papers that highlight the advances in NILM research (e.g. [16], [20], [21]).

2.4 Value Proposition of Appliance Level Disaggregated 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 behaviour, electricity auditing, demand response management and so on [2], [8].

2.4.1 Residential Demand Management

Given that I am interested in exploring the use of appliance level disaggregated electricity feedback for residential demand management, thus 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, I 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, I 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 [23] [24] and the fourth study illustrated similar level of performances [25].

A Swedish study [26], [27] 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% × 15% ≈ 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 [24] 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 [23], [25].

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 [28] [29] 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 [18] 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 [30] 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 ([24], [31]) 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 measuring the utility of disaggregated feedback; 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].

2.4.2 Value Proposition for Micro-Producers

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, I am 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 behaviours.

For testing above mentioned hypothesis Jacky Bourgeois [32] 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 behaviour 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 behaviours. 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 behaviours.

In another study Meiken [33] 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.

2.4.3 Utility Customer Engagement

Utilities old way of unidirectional transmission of electricity to traditional passive consumers is getting incompatible with present day consumers (i.e. prosumers). Because It's not only the way electricity production is changing, but also the way it is consumed, consumers are becoming prosumers having their own decentralized electricity producing sources (i.e. solar PV or wind mills) in the backyard.

A positive aspect is that electricity companies have also realized the benefits of this shift from centralized energy systems to decentralized micro grids [2], [8], [18]. This transformation in consumers' electricity consumption patterns has helped them in the design of user centric grids capable of allowing smooth bi-directional flows of electricity from grid to consumers and vice versa.

According to Yael [34] a well-functioning prosumer market is very important because it allows consumers to provide different services to the system like, demand response, energy storage, demand reduction and micro-generation. Yael [34] believes that providing electricity use feedback to consumers has become the most important tool for utilities to engage their customers and keep them loyal to their offerings.

Two consumer studies [18] conducted by Bidgely, illustrated improved levels of customer engagement, favourable consumer reaction and an 86% approval from users on making this solution available to all.

2.5 Summary from the Theoretical Framework

The above discussed literature in this thesis establishes the fact that the availability of appliance level disaggregated electricity use feedback has potential to empower households with better sense of control by making electricity consumption of households visible and providing them with constructive feedback at the same time [2]. But even after all, the final responsibility will remain with the households themselves because they are the ones who need to reduce the energy use and they must take the initiative [35], [36].

The following research gaps have been found in the published literature that I have tried to address in this thesis.

First, no controlled field trial has been conducted for investigating the value of appliance level electricity information feedback platform for solar PV micro producers (i.e. solar PV owners). And the novelty and uniqueness of our controlled field trial is that all the participants of our project are micro- producers meaning they have their own solar PV panels. Which makes our real-world deployments the first of its kind attempt to assess the value proposition of disaggregated electricity consumption feedback platform for households with solar PV panels. Furthermore, in our study participants just didn't self-selected themselves which minimizes opt-in bias significantly. Instead our screening process for recruiting participants for the study was very clear and objectively oriented [37]. Likewise, given that I was interested in assessing the value of appliance level electricity use feedback for micro producers (i.e. solar PV owners), thus I only selected participants with excessive unused solar PV production, and because they can't inject this excess electricity to the grid due to some laws preventing them in Madeira [38] that's why that unutilized electricity is simply wasted.

Consequently, I believe that appliance level electricity use feedback may help households to develop sustainable electricity use behaviours eventually improving their self-consumption (consuming everything from solar PV production). The other key distinction of our work is that they all are the real families and no one from our research has participated in the project.

Another key gap identified in the literature review that no field study has been conducted to compare the effectives of aggregated and appliance level disaggregated electricity use feedback using the same medium of delivering the feedback [8]. The fact that our project has given disaggregated electricity use feedback to our experimental group and aggregated electricity use feedback to our control group using our same web-based platform called SMILE, which makes our project stand out from the rest of the published literature.

Although the topic of electricity use reductions via appliance level electricity information platform has been explored by many researchers, very little research has focused on the value of appliance level electricity use feedback for micro-producers. As such, I believe the outcomes of our work will bring new insights and knowledge for the research community working on the topic of electricity use feedback.

3 Context and Sample Selection

In this chapter, I present clear description and scope of the thesis followed by the details about recruitment, selection, and characteristics of study sample.

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.

3.1 Overview of the Madeira Electric Grid

Madeira is a Portuguese archipelago, situated in the north Atlantic Ocean, 1000km southwest of the mainland of Portugal. The island has 270,000 permanent residents, 111,000 of which live in the capital Funchal [39].

Madeira is a total energy island which means that it is not connected to any other landmass electrically. As such, all the energy consumed in the island is generated locally. In 2017, Madeira consumed 800 GWh of electric energy. The non-domestic (e.g., tourism and commerce), and domestic sectors contribute 45% and 30% of the total consumption respectively. The remaining 25% are contributed by public lighting (9%), public buildings (8%), industry (7%), and agriculture (< 1%) [40], [41].

In Madeira, a single DSO/TSO is responsible for the activities related to production, transport, distribution, and commercialization of electric energy. It is also the entity that acquires the electric energy that is produced by private micro- and mini-producers.

The current legislation for micro-production and self-consumption of energy is defined in the Decree-Law no 153/2014 of October 20th of 2014. This legislation defines two types of units of production, 1) Unit of Small Production (UPP), and 2) Unit Production for Self-Consumption (UPAC). UPPs are units of production, based on a single technology (e.g., solar or wind). **All the energy produced by a UPP must be injected to in the Public Service Electric Grid (RESP)**. UPACs, are units of production that can be either off-grid or grid-connected. **The energy produced by a UPAC, must be first used for self-consumption**, and only then injected to the grid.

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

In Madeira Island, since 2014, new UPPs and UPACs are not allowed to feed-in excess production to the local grid, thus excess generation is wasted. The main reason for this change in the local legislation is to protect the grid from the issues associated with the intermittent and uncertain nature of renewable production from solar in a total energy system.

Due to such a constraint new UPACs are sized to maximize self-consumption and minimize excess production. Furthermore, counterintuitively, in a period that one should expect an explosion in the number of micro-producers leveraged by the relatively low prices of solar PV technologies, Madeira Island is experiencing a stagnation on the number of new solar PV installations [40], [41].

3.2 Smart IsLands Energy systems in Madeira Island

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.

To this end, within the SMILE project, several domestics UPACs were recruited to take part of the Madeira Island tested, from which four (4) will be selected to have their installations upgraded with the installation of a BESS.

3.2.1 Participant Recruitment and Sample Selection

The local SMILE team recruited participants using different platforms such as online advertisement campaigns (Figure 3.1), handing over formal letters, contacting people directly on their phones, organizing information sessions about the study in collaboration with local DSO/TSO (EEM) [37]. Ultimately, the SMILE team was able to recruit 12 domestics UPACS (please refer to [42] for additional details about the participants recruitment.).

Figure 3.1 Advertisement for recruitment of participants

After an initial period of data collection (see Section 5.1.1 for more details about the electric energy consumption and solar PV production data collection), an in-depth analysis of the production and consumption was conducted for each of the participants. The objective of this analysis was to select the four (4) participants that could benefit most from installing a battery energy storage system. Extensive details about this process are publicly available in the following project deliverables [43], [44]. Table 3.1 presents some details of the recruited participants. Ultimately, the four participantts with more surplus solar PV were selected to receive a battery. These participants are highlighted in red.

Table 3.1 Demographics and electric Installation details of the recruited participants

ID (ID in [42])	People	Ages	Occupation	PPC (kVA)	Inst. PV (kWp)	Excess Prod. (%)
UPAC 1 (A)	4	44, 42, 14, 11	Nature Watcher	6.9	0.39	2
UPAC 2 (B)	4	84, 47, 48, 22	Teacher	6.9	1.5	27
UPAC 3[a]	2	49, 37	Electrical Engineer	5.75	1	11
UPAC 4 (C)	4	56, 52, 23, 21	Retired	6.9	0.5	29
UPAC 5 (D)	3	42, 41, 6	Nurse	6.9	1.25	31
UPAC 6 (E)	2	74, 32	Unemployed	10.35	2.7	63
UPAC 9 (G)	3	51, 45, 20	Construction Worker	6.9	4.5	69
UPAC 10 (H)	2	64, 64	Electrician	6.9	1.5	41
UPAC 11[a]	6	10, 41, 50, 5, 5, 5	Electrical Engineer	6.9	1.5	2
UPAC 12 (I)	4	55, 50, 20, 15	Teacher	6.9	3	48
UPAC 13 (J)	5	41, 42, 13, 10, 7	Businessman	10.35	1.5	5
UPAC 14 (K)	4	55, 55, 28, 19	Government Worker	3.45	0.75	31

[a] Please note that participants UPAC 3 and UPAC 11 were not part of the study in [42]. This happened due to the difficulty in interviewing these participants at that time. Note also that participant F in [42] opted out of the project before the work in this thesis.

After this selection, the remaining eight (8) participants were the natural candidates to participate in the individual appliance consumption eco-feedback study, **since they still had some surplus but not enough to justify the installation of a battery**. Nevertheless, two of them were not eligible. One because it had no surplus production (UPAC 11), the other because the householders were not living in the house for the majority of the time (UPAC 5). Ultimately, I was left with the six participants that were selected to have their eco-feedback systems enhanced with individual appliance consumption information. As for the remaining six participants, they were assigned to the control group by continuing to receive only feedback on the aggregated electric energy consumption and solar PV production. Table 3.2 presents the final distribution of the participants. Our sample have been assigned some coded identity ensuring privacy compliance, hence they would be referred with their coded identity in this document.

Table 3.2 List of the Participant of the study (coded)

Experimental Group		Control Group	
Coded Identity	Original Identity	Coded Identity	Original Identity
A	UPAC 1	G	UPAC 2
B	UPAC 3	H	UPAC 5
C	UPAC 4	I	UPAC 6
D	UPAC 10	J	UPAC 9
E	UPAC 13	K	UPAC 11
F	UPAC 14	L	UPAC 12

3.2.2 Sample Description

3.2.2.1 Demographics of Experimental Group

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 I talk about the age group then I 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).

3.2.2.2 Demographics of Control Group

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 I talk about the age group then I 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 (see Table 3.1 for more details).

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 [38].

4 Research Methodology

In this section, I describe all the necessary systematic stages which were chosen for developing the effective research methodology to test our hypothesis along with the rationale for each level of methodological decisions.

4.1 Research Model

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 [45]. Therefore, research onion model was used for developing the effective research methodology to test our hypothesis.

The research onion model breaks research methodology into the following parts:

- Research Philosophy (Outer Layer)
- Research Approaches
- Research Design
- Time Horizons
- Data Collection instruments (Inner Layer)

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 analysed 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.

4.2 Data Collection Instruments

As stated above the implementation of research onion model for developing effective research methodology comes very handy if implemented backwards beginning from the selection of type of data collection instruments. Therefore, I started by shortlisting the data collection instruments needed to answer our research questions. After going through the published literature on electricity conservation through electricity information feedback, it has been learnt that the ideal way to test and investigate our hypothesis would be to do it with the help of both quantitative and qualitatively data.

4.2.1 Quantitative Data

The following types of quantitative data were collected: (1) monthly electricity consumption data from smart meters, (2) near-real time appliance level electricity use data using plug-level sensors, (3) Pre and post knowledge and appliances surveys which would be discussed in details in data collection chapter.

The quantitative data of households' electricity consumption would help us understand if our independent variable (i.e. appliance level electricity information feedback) has any effect on the dependent or variable of our interest (i.e. reduction of electricity usage or electricity bills or consuming more from PV production).

4.2.2 Qualitative Data

The following types of qualitative data were collected: (1) behaviours questionnaire, (2) post experiment detailed interviews which will be discussed in details in the data collection chapter.

Given that, electricity conservation involves human behaviour and quantitative methods alone have struggled to explain the human behaviour in the past, hence, I deemed to include qualitative data methods as well to contextualize our quantitative findings.

4.3 Research Approach

There could be two research approaches: deductive research approach and inductive research approach depending on the type of the study and objective whether you want to test already known hypothesis (deductive approach) or want to build new hypothesis from available information/data. I have selected deductive research approach because it matched perfectly with the scope of our research project because I already had hypothesis in our hand and just wanted to analyse the collected data from selected data collection instruments for either accepting or rejecting our hypothesis.

4.4 Research Design

When it comes to finding causality or establishing a cause-effect relationship between variables, no other research design (i.e., survey design) could outperform experimental design.

Controlled experimental setting with an experimental and a control group have been designed for examining the cause-effect relationship of desired variables. The presence of control group in the study is to account for the influence of unforeseen external events on the results of experimental group.

Given that experimental setting always requires at least two variables for determining the usefulness and effectiveness of the intervention. Thus, following are two variables of interest.

- Independent variable (i.e. appliance level electricity information feedback)
- Dependent variable (i.e. changes in electricity usage practices).

Similar to most controlled field trials, our study design consists of two groups: an experimental group and a control group. The idea was to provide appliance level electricity use feedback to the experimental group (i.e. micro-producers with surplus electricity) and see if it could help them to adopt sustainable electricity use practices by shifting electricity intensive activities from night to during the day when there is excessive unutilized electricity produced by solar panels. On the other hand, the control group had access to only aggregate electricity use feedback to not let them be influenced by appliance level electricity use feedback. However, both the groups would be using the same web-based platform (i.e. the SMILE eco-feedback) thus reducing any potential bias related to the feedback platform. The only difference is that the experimental group would be exposed to appliance level disaggregated electricity use feedback while control group would be given aggregated electricity information feedback.

4.5 Reliability and Validity of a Research

Our experimental setting has clearly defined independent variable (i.e. appliance level electricity information feedback) and dependant variable (i.e. reduction of electricity usage or electricity bills or consuming more from PV production) that's important for making any research outcome valid and generalized to other relevant settings. One thing that is very important when dealing with experimental is to ensure that measured changes of dependant variable, was actually caused by the manipulation of the independent variable or some other factors.

Valid and reliable research outcome requires dedicated and vivid research methodology with all the necessary stages provided with solid explanations and justifications for each level of methodological decisions. So, that in future if some researcher choses to use the same data collection instruments and same research strategy should reach same conclusion.

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.

In this chapter, I have describe all the details about the different types of data collection instruments both qualitative and quantitative which were selected for testing our hypothesis about assessing the utility of appliance level electricity use feedback for micro-producers (photovoltaics owners), along with solid explanations and justifications for selecting those types of data instruments. I have also described the methods, and tools used for collecting these types of data collection instruments. Finally, I concluded this chapter by describing the data visualization of both aggregated and disaggregated electricity use information elicited by our feedback system.

5.1 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.

5.1.1 Electricity Consumption and Solar PV Production Data

In the scope of the SMILE project, electricity consumption and solar PV production was monitored using a custom created monitoring system. The system was composed of Carlo Gavazzi smart-meters, and a Raspberry PI micro-computer that acted as a gateway puling measurement from the smart-meters and uploading these measurements to a cloud-based Energy Management System (EMS). The ModBUS RTU[2] serial protocol was used for establishing the communication between the two devices for smoothly transferring the household's electricity consumption data from the households to the gateway. The communication with the EMS was performed using 3G hotspots connected via USB [38]. The

[2] ModBUS RTU, https://www.modbustools.com/modbus.html

electricity consumption and solar PV production data is measured at the granularity of 1Hz, but only 1-minute averages are uploaded to the EMS.

Figure 5.1 presents examples of the energy monitoring system deployed in three of the participating prosumers. Extensive details of the monitoring platform are out of the scope of this thesis, but can be found in the public project deliverable [37].

Figure 5.1 Examples of the Energy Monitoring System deployed in three UPACs

5.2 Individual Appliance Consumption Data

Appliance level electricity consumption monitoring especially through non-intrusive methods (i.e., NILM) has become very attractive topic for many researchers because it boasts near-to-similar appliance level electricity disaggregation like plug-level sensors but without requiring expensive sensors hardware. Unfortunately, at the moment, it is not easy to find NILM solutions that are reliable enough to be used in a live deployment because of lack of availability of properly labelled data sets to properly evaluate the performance of such techniques [46].

I have selected a plug-level solution for collecting appliance specific electricity information because it offered us twofold benefits: firstly, it provided us reliable monitoring results, which is not yet possible using NILM; secondly, it represented an opportunity to gather and store good quality labelled datasets which in future could be used for doing similar appliance level disaggregation through non-intrusive methods (NILM) [46].

The individual appliance consumption data was collected using the Plugwise[3] system, with a slightly modified version of the gateway presented in [46]. Plugwise is a commercially available distributed sub-metering platform that consists of three main components: smart plugs, stick to enable the communication between the plugs and the gateway via ZigBee[4], and the *source* software that is used for configuration and eco-feedback purposes.

The gateway (Figure 5.2 – left), was configured to read the individual plugs (Figure 5.2 – right) at the frequency of 1Hz, and to upload the averaged readings to the EMS once every minute. The communication between the gateway and the EMS was performed using Wi-Fi.

Figure 5.2 Individual appliance consumption collection setup: gateway (left), smart plugs (right)

5.2.1 Monitored Appliances

The number of individual loads monitored in each household varied between 10 and 17. Table 5.1 lists the appliances that were monitored in each house. Note the presence of empty plugs that were deployed in order to increase the range of the Zigbee mesh.

Table 5.1 Monitored appliances of participants

Appliance	**Participant**					
	A	**B**	**C**	**D**	**E**	**F**
Blender						X
Clothes Washer	X	X	X	X		X
Coffee Maker	X	X	X	X X	X	

[3] Plugwise, https://www.plugwise.com/en_US/
[4] Zigbee Alliance, https://zigbee.org/

Appliance	Participant					
	A	B	C	D	E	F
Cooking Machine		X	X		X	
Compressor				X		
Dishwasher				X		
Freezer	X X			X	X	
Fridge	X	X	X	X X	X	X
Game Console	X X					
Hair Dryer						X
Iron	X		X	X	X	
Kettle		X				X
Laptop	X			X	X	X X
Microwave			X	X		X
Oven						X
Stove				X		
TV	X X	X X	X	X	X X	X
Toaster			X	X	X X	X
Empty plugs		X X	X X	X X X		X X

5.3 Pre- and Post- Appliance Consumption Knowledge Survey

According to Shahzeen [9] households often misperceive their electricity use which could be one of the main reasons stopping them from adopting more sustainable electricity use practices to decrease their electricity use.

Therefore, I have designed and conducted an online survey for assessing the knowledge of our sample about electricity usage of major household appliances. In this online survey, I provided our participants with a list of electric appliances (see Table 5.2), and asked the following questions with respect to each individual appliance:

Table 5.2 List of Appliances used for the survey

Air Conditioner	Coffee Maker	Iron	Stove
Heater	Dishwasher	Blender	TV
Lamp – CFL	Freezer	Clothes Dryer	Toaster

Laptop	Fridge	Clothes Washer	Vacuum Cleaner
Microwave	Game Console	Water Heater	

Question 1: *"How much do you think the appliance shown below consumes in one hour?"*

Possible Answers: Likert scale between 1 (very little consumption) and 10 (a lot of consumption).

Question 2: *"How easy it was to rate the consumption level of this appliance?"*

Possible Answers: Very Difficult (1), Difficult (2), Normal (3), Easy (4), Very Easy (5)

Question 3: *"Was your answer based on a guess or knowledge?"*

Possible Answers: Random Guess (1), Educated Guess (2), Knowledge (3)

Question 4: *"How confident are you with your answer?"*

Possible Answers: Very Unsure (1), Unsure (2), Sure (3), Very Sure (4)

Figure 5.3 shows a sequence of screenshots of the UI when answering the questions for a particular appliance. It is important to remark that once a reply was given it was not possible to change it. Furthermore, the appliances were presented in the same order to all the participants, more concretely, ordered alphabetically from A to Z.

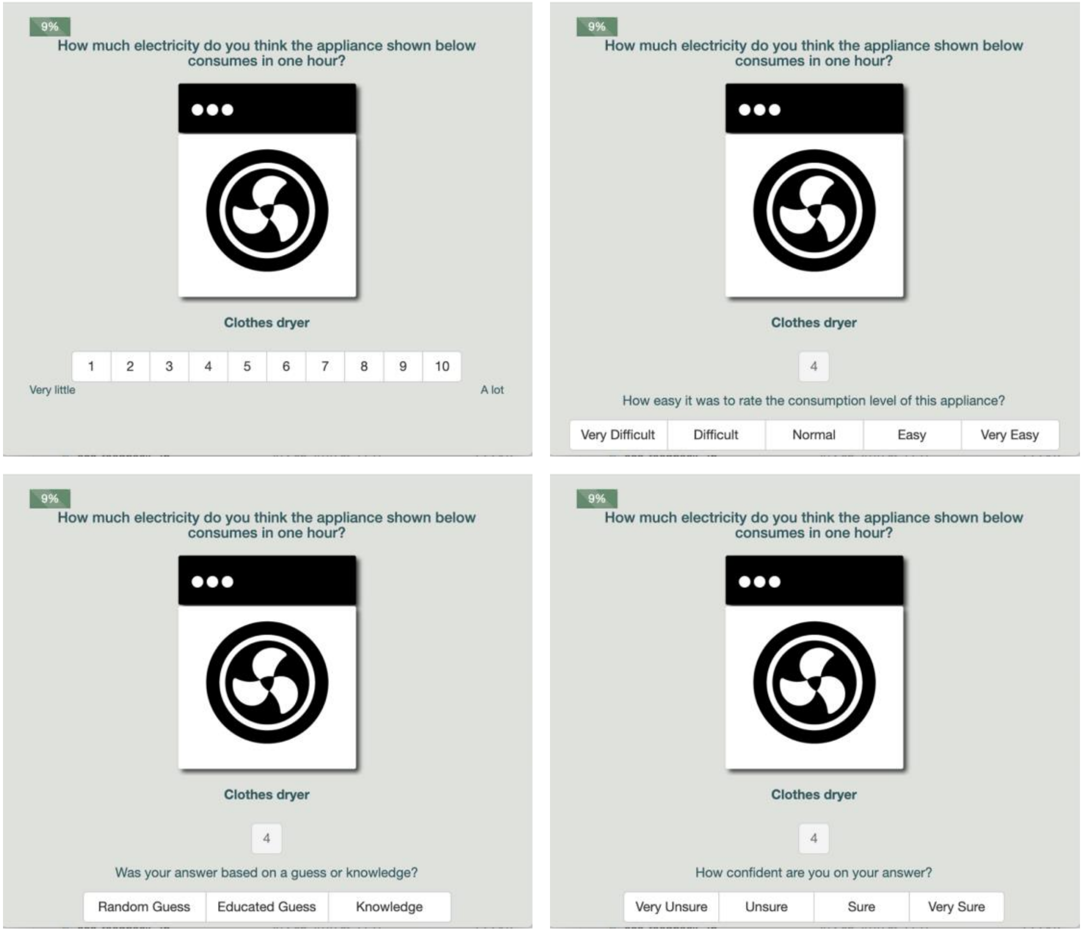

Figure 5.3 Sequence of questions: question 1 (top left), question 2 (top right), question 3 (bottom left), question 4 (bottom right).

I have 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 appliances electricity consumption or a specific way of using those appliances and how it affects the total electricity consumption and the money spent [2].

5.4 Qualitative Data Collection Instruments

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

- Behaviours Questionnaire
- Post Intervention Interview

5.4.1 Behaviors Questionnaire

Given that the main objective of conducting this controlled field study is to investigate if households with solar PV panels when provided with near-real time appliance level electricity information feedback could reduce electricity usage or at least be more self-sufficient (consume maximum from PV production) by adopting more sustainable electricity use behaviours. And as it is already reported in published literature that improved and personalized electricity feedback may help households to develop sustainable electricity use behaviours eventually optimizing their electricity use [2], [6]–[10]. For the purpose of understanding household perceptions about the adoption of certain sustainable electricity use behaviours associated with the photovoltaic proliferation in particular.

After a brainstorming session I have defined two categories of electricity use behaviours which could lead to photovoltaic proliferation: one category of behaviours represented activities focused on **shifting of electricity usage** (Table 5.3) from periods without production to during the day when there is excess solar production. The other category of behaviours focused on **replacing electricity intensive activities** with alternative sustainable practices like playing board games instead of PlayStation (Table 5.4).

Table 5.3 List of shifting behaviours category

Behaviour 1	Playing game console during the day
Behaviour 2	Cooking dinner earlier
Behaviour 3	Using dishwasher for doing dishes during the day
Behaviour 4	Doing laundry during the day (both washing and drying)
Behaviour 5	Using iron for pressing clothes during the day
Behaviour 6	Using a vacuum cleaner for cleaning house during the day
Behaviour 7	Charging EV during the day
Behaviour 8	Turn of freezers during the night to have them on during the day
Behaviour 9	Whenever possible take showers during the day

Table 5.4 List of replacing behaviours category

Behaviour 1	Playing board games instead of game console at night
Behaviour 2	Preparing less energy intensive meal or with a slow cooker
Behaviour 3	Doing dishes by hand if at night
Behaviour 4	Postpone laundry until full loads available
Behaviour 5	Postpone ironing until full loads available
Behaviour 6	Don’t use a vacuum cleaner
Behaviour 7	Using public transport once a week while the EV is charging
Behaviour 8	Avoid unnecessary opening of the freezer doors
Behaviour 9	Take a shorter shower instead

I asked our participants to rank the easiness and usefulness of adopting each behaviour under these two categories. A Likert-scale from 1 = (Very Difficult), 2 = (Difficult), 3 = (Don't know), 4 = (Easy), 5 = (Very Easy) for the former. Another Likert-scale from 1 = (Extremely Useless), 2 = (Useless), 3 = (Don't know), 4 = (Useful), 5 = (Extremely Useful) was used for the latter.

5.4.2 Post Intervention Interview

All of our participants were interviewed post intervention. Interviews were designed to be semi-structured in nature, and were conducted to understand more about the barriers and motivations of householders for engaging in sustainable electricity use behaviours. Each interview had a duration between 30 and 45 minutes.

The interviews evaluated five aspects concerning the self-consumption system installed in participants' homes:

- Participants perceived value of appliance level electricity use feedback
- Experience with UI Design, presentation of appliance level electricity use feedback
- Strategies used to optimize their production from photovoltaics
- Routines and changes
- Motivations & Barriers

5.5 Eco-Feedback User Interfaces

After the installation of the energy monitoring infrastructure, all the participants in the SMILE project were provided with eco-feedback on their aggregated energy consumption and solar PV production.

Along with aggregated energy consumption feedback, the participants in this study were also given feedback in individual appliances consumption.

It is important to remark, that in both situations the eco-feedback was provided using the same channels, in this case a fully responsive web-based platform. Below I present the eco-feedback user interfaces in greater detail.

5.5.1 Aggregated Eco-Feedback

Given that individuals in residential setting exhibit varied attitudes and understanding about electricity usage [47]–[49], thus it was decided from the beginning that in our feedback system household electricity consumption information must be elicited in more than one forms to make it relevant to the maximum number of individuals. Our feedback system illustrated household electricity consumption information in following options: 1) Energy and power in terms of kWh/kW, 2) cost in €, and 3) environmental impact in terms of CO_2. See Figure 5.4 for a screenshot showing how this information is displayed.

Figure 5.4 A screenshot of the "analytics" page showing household electricity consumption.

Our eco-feedback platform provides feedback in the following modes: 1) real-time, 2) historical, and 3) comparisons, as recommended in the published literature [2], [50], [51]. The different visualizations depict consumption (grid + solar PV), solar PV production, and wasted solar PV production (i.e., injected in the grid for free).

5.5.1.1 Real-time eco-feedback

The real-time part of the feedback elicited current consumption and production including an overview of recent energy use (last hour and current day/week/month) (see Figure 5.5, Figure 5.6, Figure 5.7, and Figure 5.8).

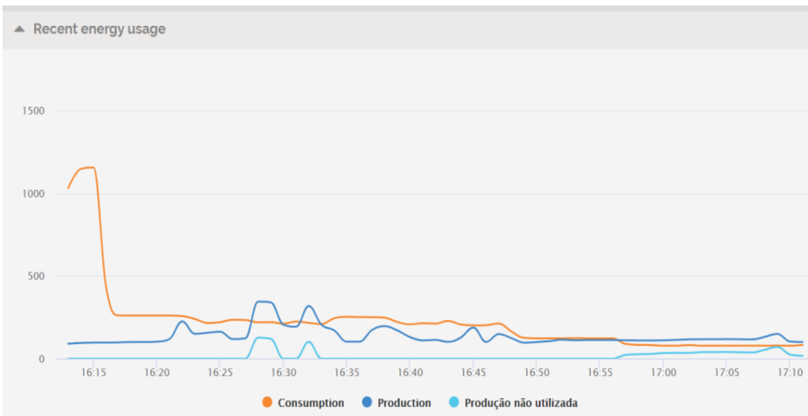

Figure 5.5 Recent energy use (last hour)

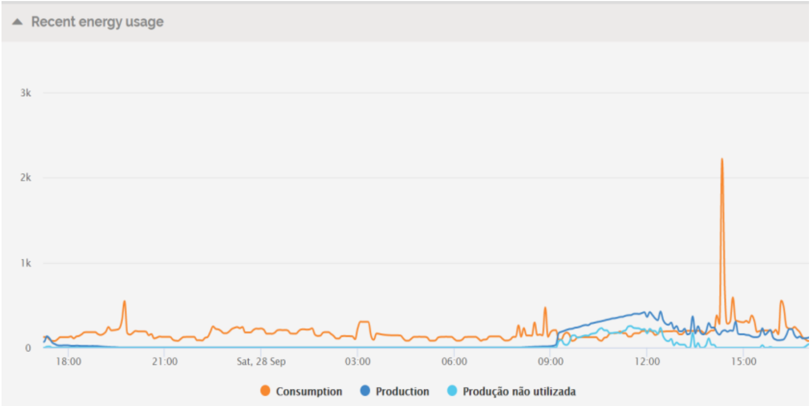

Figure 5.6 Recent energy use (current day)

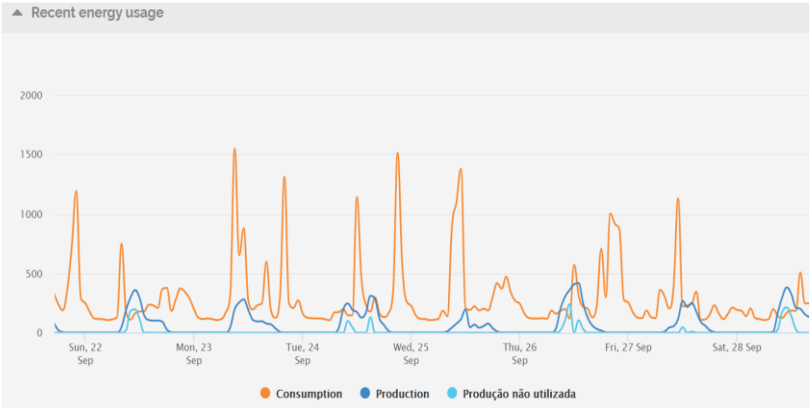

Figure 5.7 Recent energy use (week)

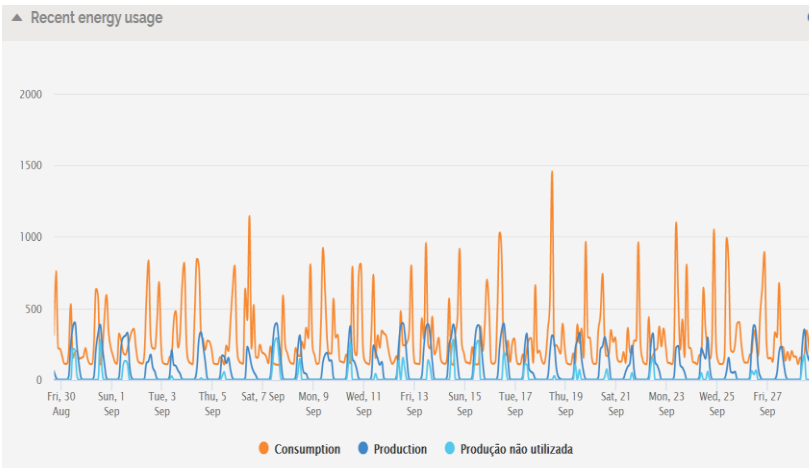

Figure 5.8 Recent energy use (month)

5.5.1.2 Historical eco-feedback

Our eco-feedback user interface also contains historical features for presenting the historical energy consumption and production from PV of the participants. The historical part of the feedback presents energy consumption and production from PV in (day/week/month) (see Figure 5.9, Figure 5.10, Figure 5.11).

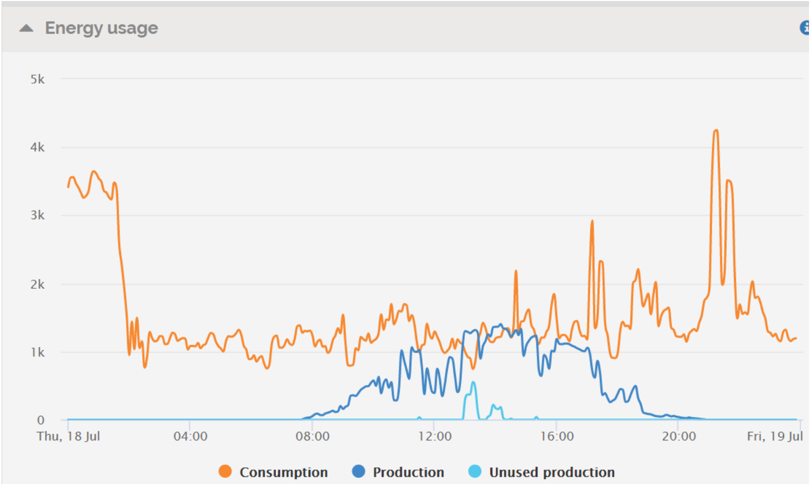

Figure 5.9 Historical Energy Use (Day)

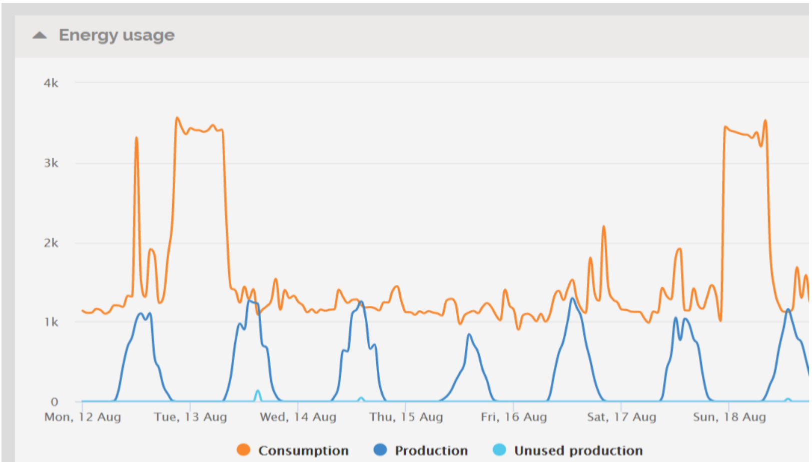

Figure 5.10 Historical Energy Use (Week)

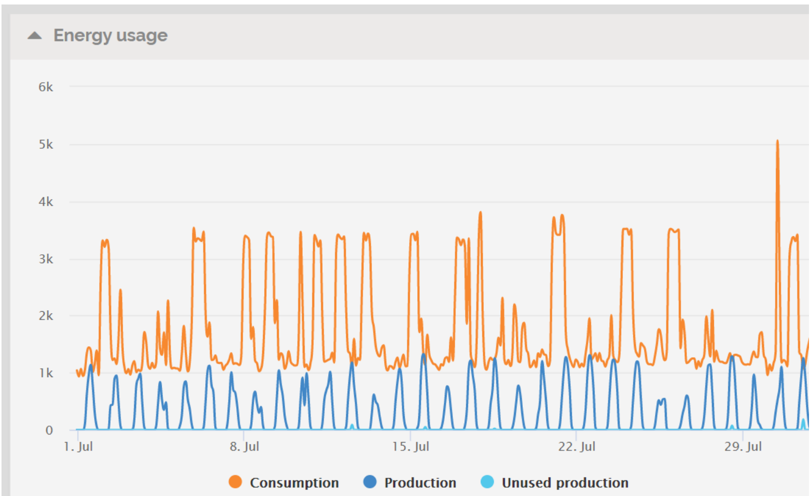

Figure 5.11 Historical Energy Use (Month)

5.5.1.3 Comparisons

For the comparison part, as Fischer pointed [11], there are two main types of comparisons: 1) historical comparison (comparison between one's current and past data), and 2) normative comparison (comparing one's data to that of other households).

Both types of comparison feedbacks are valid and have been implemented in various field studies but our feedback system only represented historical (-self) comparison (Figure 5.12). Because when household are compared with other household or neighbors they tend to question the validity of the group they are being compared with [47].

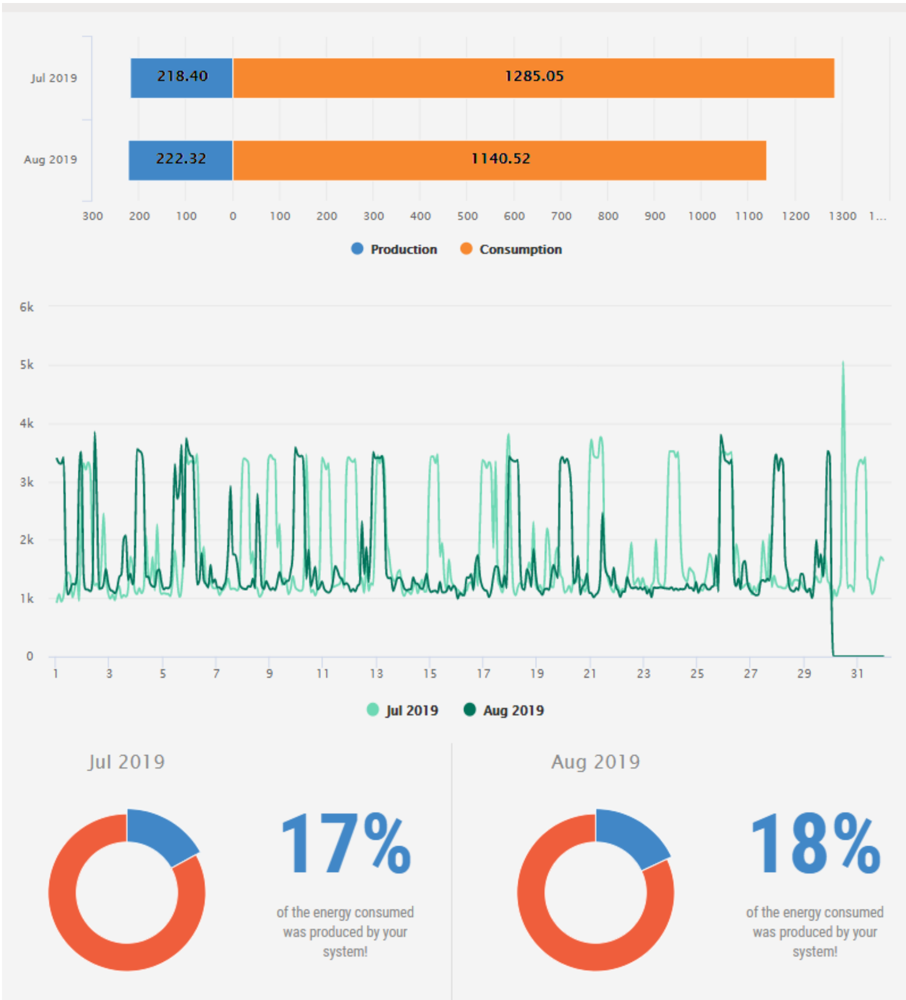

Figure 5.12 the three visualization for Historical comparisons

5.5.2 Individual Appliance Eco-Feedback

As Melanie [6] suggested, improved and personalized electricity consumption feedback may help households to develop sustainable electricity use behaviours. But the usefulness of such a feedback to a great extent depend on the way that that information is presented [52], [53].

5.5.2.1 Proposed Designs

Given that if householders can't understand the way feedback is presented, then the usefulness of such an information platform in helping household in making informed decisions and adopting more sustainable electricity use behaviours is compromised. Therefore, I spent a great amount of time finding the best way to present appliance level electricity consumption feedback to our subjects. In the beginning, different options (charts/diagrams) were considered for presenting the individual appliances electricity use data. The options which came under consideration while designing user interface for appliance level electricity consumption data are stacked charts (Figure 5.13 Figure 5.14) , Sankey diagrams (Figure 5.15 Figure 5.16), and Marimekko chart (Figure 5.17).

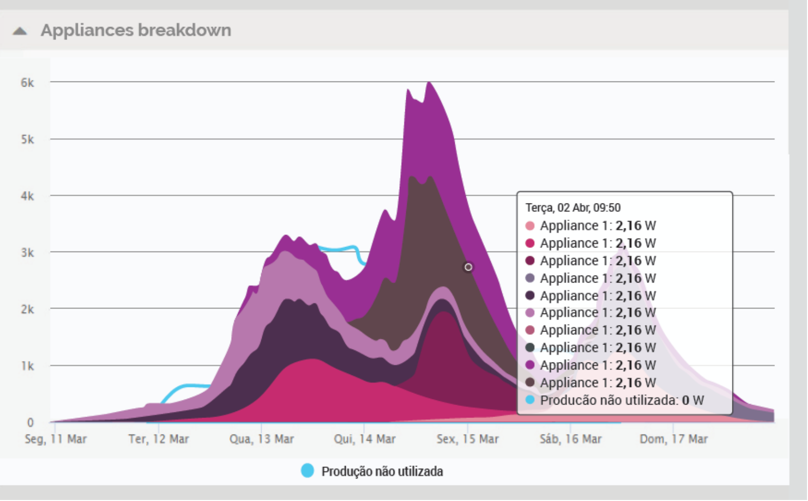

Figure 5.13 Stacked Line Chart showing breakdown of appliances

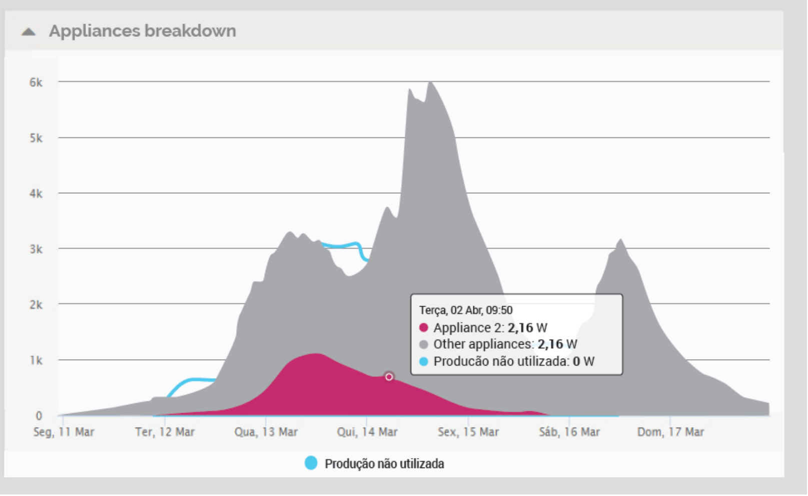

Figure 5.14 Stacked Line Chart showing energy use of an appliance

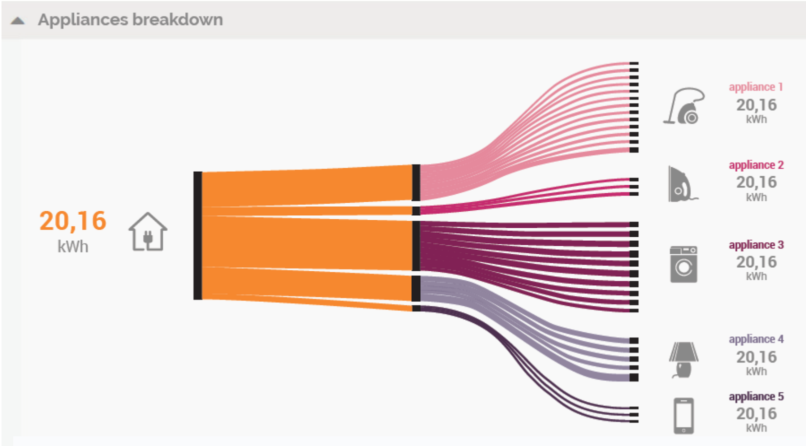

Figure 5.15 Sankey Diagram showing appliances breakdown

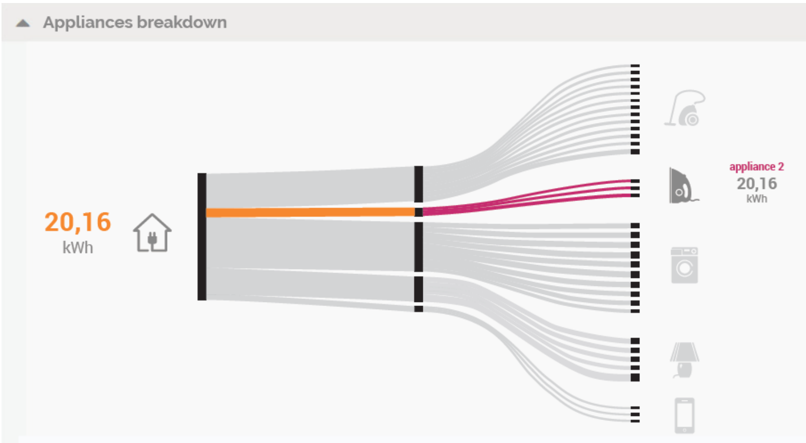

Figure 5.16 Sankey Diagram showing energy use of an appliance

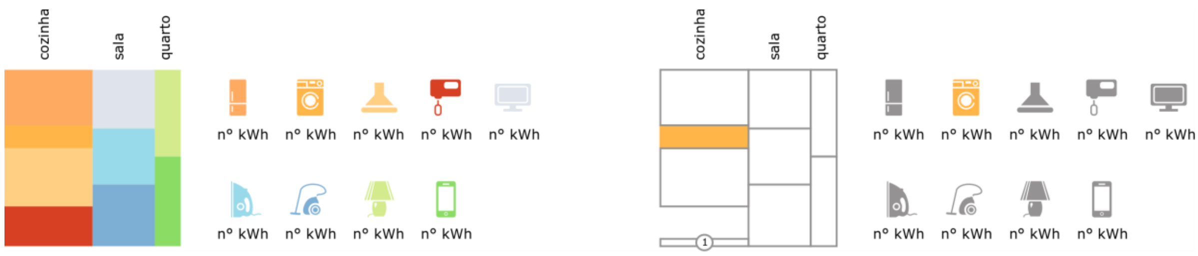

Figure 5.17 Marimekko chart showing appliances breakdown

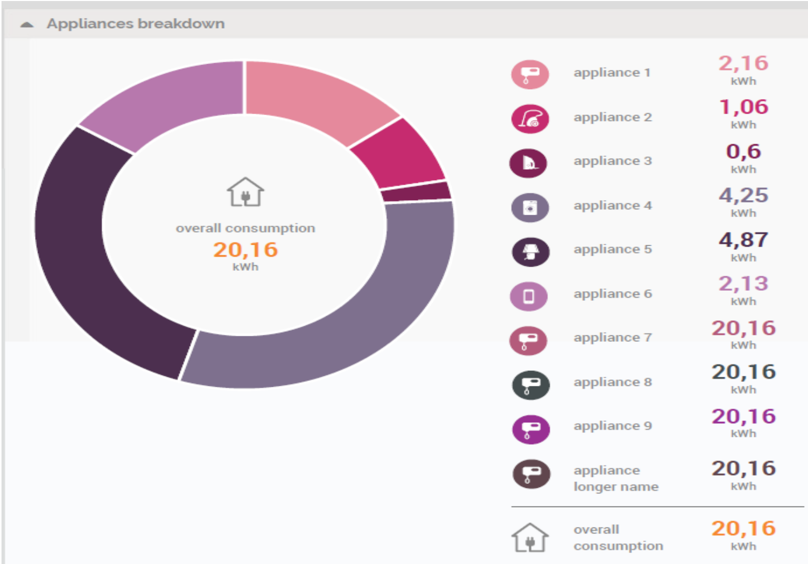

Figure 5.18 Pie Chart showing appliances breakdown

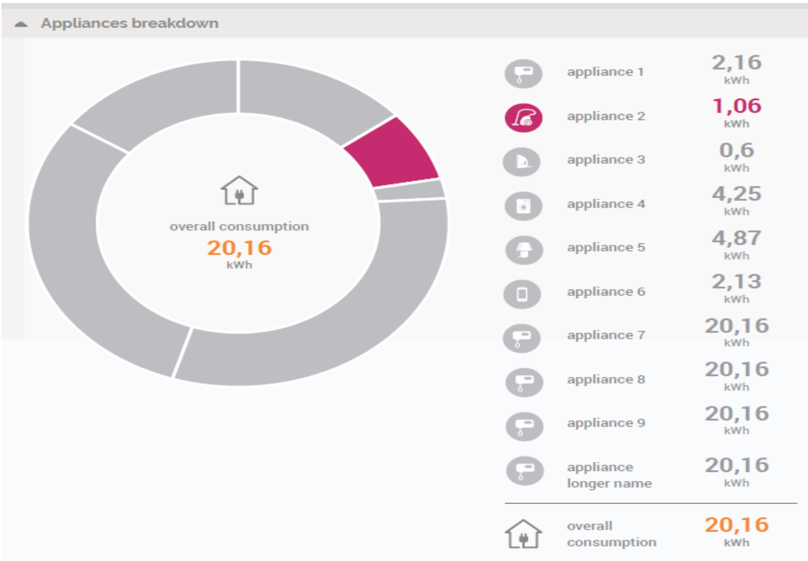

Figure 5.19 Pie Chart showing energy use of an appliance

5.5.2.2 Implemented Designs

In the end, the pie chart representation was selected for presenting appliance level electricity information for our feedback system. The main reason for this decision is the fact that this type of chart is ideal for eliciting information breakdowns. Furthermore, it is more standard form of visualization, thus less complex and easier for every participant to grasp [5]. The different components of the deployed user interfaces are provided below.

The main screen shows the breakdown of recent electricity use by appliances (Figure 5.20). This is done in terms of instantaneous consumption (in Watts) and accumulated energy consumption (in kWh). It is possible to see the electricity consumption breakdowns of appliances for day, week and month intervals.

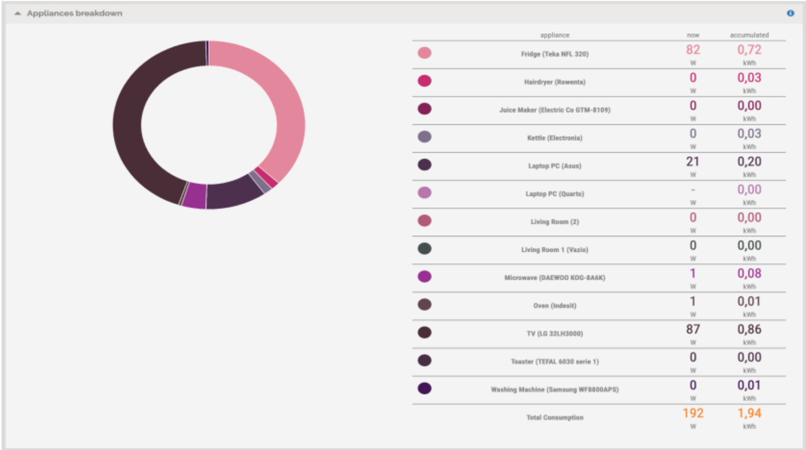

Figure 5.20 A screenshot of the "analytics" page showing breakdown of specific appliances

Once the user selects an appliance, either in the chart to the left, or the list to the right (Figure 5.20), two things happen as shown (Figure 5.21): 1) the pie chart highlights the electricity use of that specific selected appliance and displays what percent of total electricity consumption belongs to the selected appliance, and 2) a line chart appears below the pie chart to display the electricity use of that specific appliance against the excess electricity from PV production over time.

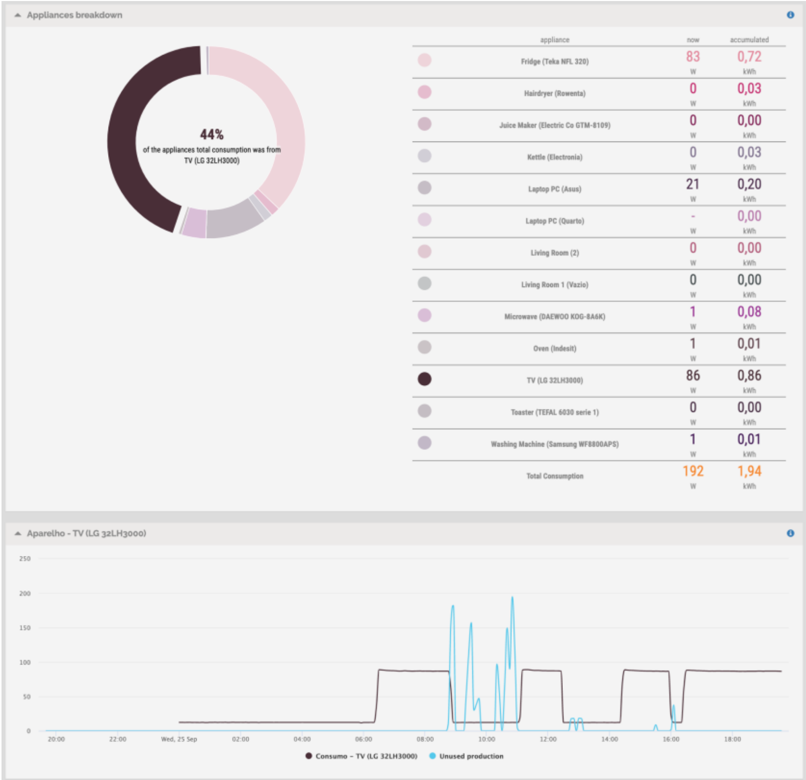

Figure 5.21 A screenshot of the "analytics" page showing breakdown of specific appliances

6 Data Analysis and Discussion

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

6.1 Knowledge Survey Results

I have conducted an online survey, in which I provided our participants with a list of electric appliances (Table 5.2), and asked them questions (Figure 5.3) to assess their knowledge about domestic appliances electricity usage.

I have 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.

6.1.1 Pre-intervention survey results

In order to assess the response of each participant to the online survey questions a baseline scale was created to compare the reported consumption rates (Question 1) with actual consumption rate of the appliances. For this purpose, the baseline data was sorted according to the average consumption rate of each appliance provided in the Non-Intrusive Load Monitoring (NILM) Wiki web site and then divided them into 10 non-equidistant groups in order to correspond with the 10-point Likert scale used in the survey [54].

Figure 6.1 illustrates a summary of the obtained ratings for the pre-intervention survey. The appliances appear sorted from high to low consumption (from left to right) according to our participants reported ratings.

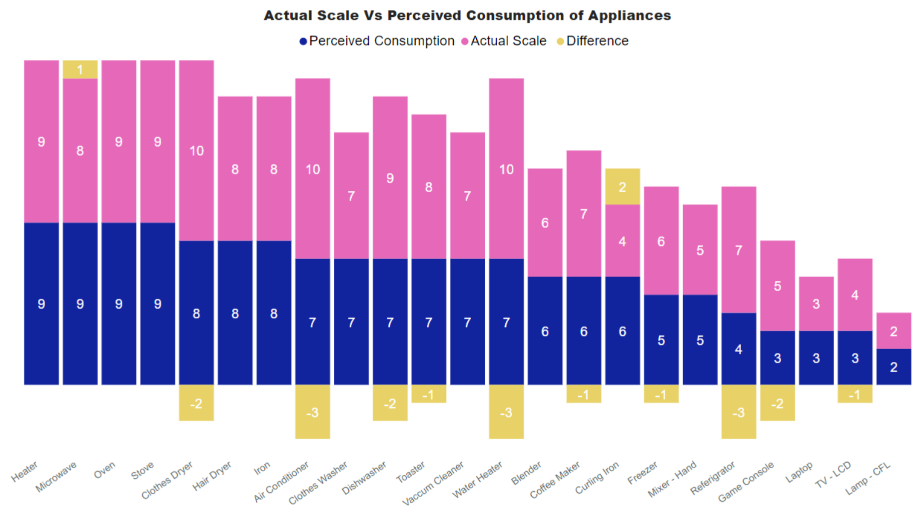

Figure 6.1 Pre-intervention survey results about individual appliance consumption.

If I look at the (Figure 6.1) then I can see that participants have under-estimated 10 out of 23 appliances and over-estimated only 2 out of 23 appliances. So, there seem a clear visible tendency of under-estimation by participants. Some of the major appliances which were under-estimated by the participants in the online survey are following:

- Air conditioner
- Clothes dryer
- Water heater
- Dishwasher
- Toaster
- Coffee maker
- Refrigerator
- Freezer
- Game-console

Figure 6.2 illustrates a summary of all the responses to all the questions in pre-intervention survey. Including responses to follow up questions to Question 1 about reporting consumption of different domestic appliances 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.

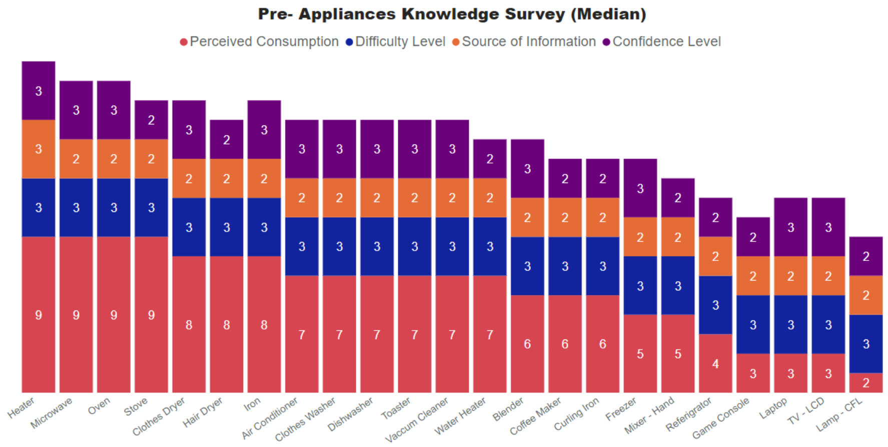

Figure 6.2 Pre-intervention survey results about individual appliance consumption.

Firstly, for the responses of Question 2 about the difficulty level, the median for all appliances is 3 indicating that most of the participant's didn't feel that it was difficult or easy to report the consumption of different domestic appliances.

Secondly, for the responses of Question 3 about the source of information, the median for all appliances is 2 indicating that most of the participants had educated guesses in reporting consumption of different domestic appliances.

Last but not the least, for the responses of Question 4 about the confidence level, the median for all appliances varies between 2 to 3 meaning that for some appliances participants were unsure and for others they were sure in reporting consumption.

6.1.2 Post intervention survey results

Figure 6.3 illustrates a summary of the obtained ratings for the post-intervention survey. The appliances appear sorted from high to low consumption (from left to right) according to our participants reported ratings.

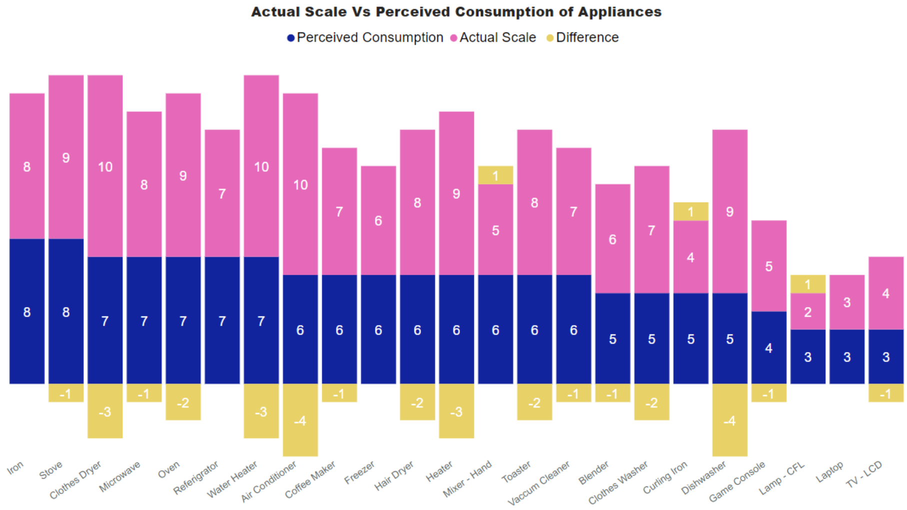

Figure 6.3 Post- intervention survey results about individual appliance consumption.

If I look at the post intervention survey results (Figure 6.3) and compare it with the pre-intervention survey results (Figure 6.1) then I can see that the tendency of under-estimation have even increased. Participants have under-estimated 16 out of 23 appliances and over-estimated only 3 out of 23 appliances.

Most of the appliances which have been under-estimated in both pre-intervention and post-intervention survey results are very electricity intensive. Therefore, misperceiving electricity use of such major high electricity consuming appliances could be one of the reasons stopping household from taking actions to decrease their electricity use.

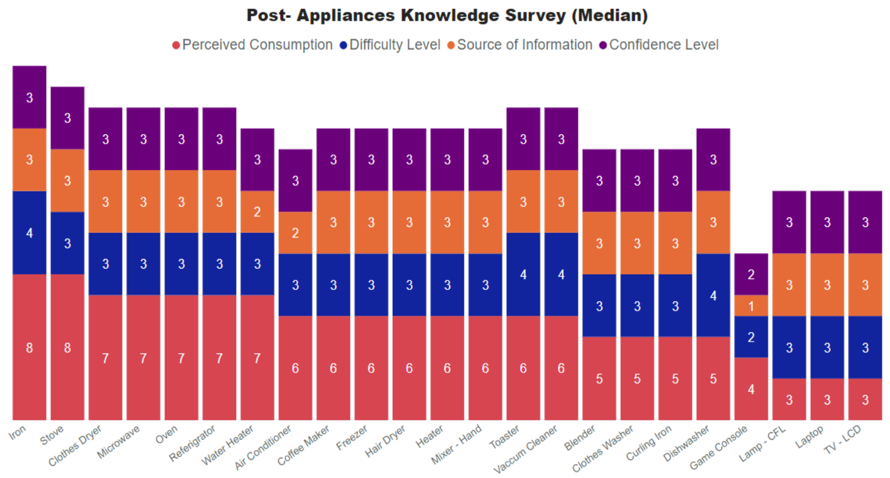

Figure 6.4 Post intervention survey results about individual appliance consumption.

Figure 6.4 illustrates a summary of all the responses to all the questions in the post intervention survey. Including responses to follow up questions to Question 1 about reporting consumption of different domestic appliances 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.

Firstly, for the responses of Question 2 about the difficulty level, the median for most of the appliances is 3 indicating that most of the participant's didn't feel that it was difficult or easy to report the consumption of different domestic appliances. However, median for some appliances (Iron, toaster, and vacuum cleaner) has changed from 3 to 4 indicating that most of the participant's found it easy to report consumptions for these appliances.

Secondly, for the responses of Question 3 about the source of information, the median for most of the appliances has changed from 2 (pre-intervention survey) to 3 (post-intervention survey) indicating that most of the participants think that they reported consumption of those appliances based on their knowledge rather than educated guesses (pre-intervention survey).

Last but not the least, for the responses of Question 4 about the confidence level, the median for all appliances is 3 except one (game console -2) meaning that most participants were sure when reporting consumption of different domestic appliances. It is also interesting to note that for pre-intervention survey median for appliances varied between 2 to 3 meaning that for some appliances participants were unsure and for others they were sure in reporting consumption.

6.1.3 Discussion

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.

6.2 Behaviours Survey Results

To understand the participants stated vs revealed preferences, a Likert-scale from 1 to 5 was created to investigate perceived easiness, and usefulness of adopting sustainable electricity use behaviours associated with the photovoltaic proliferation in which participants had to rank on a Likert-scale from 1 to 5, the perceived easiness and usefulness or uselessness of adopting the behaviors listed in Table 5.4 and Table 5.3.

6.2.1 Shifting Behaviours

Figure 6.5 presents the results obtained for the shifting behaviours category. The graph refers the perceived easiness or difficulty as well as perceived usefulness or uselessness of adopting such behaviours.

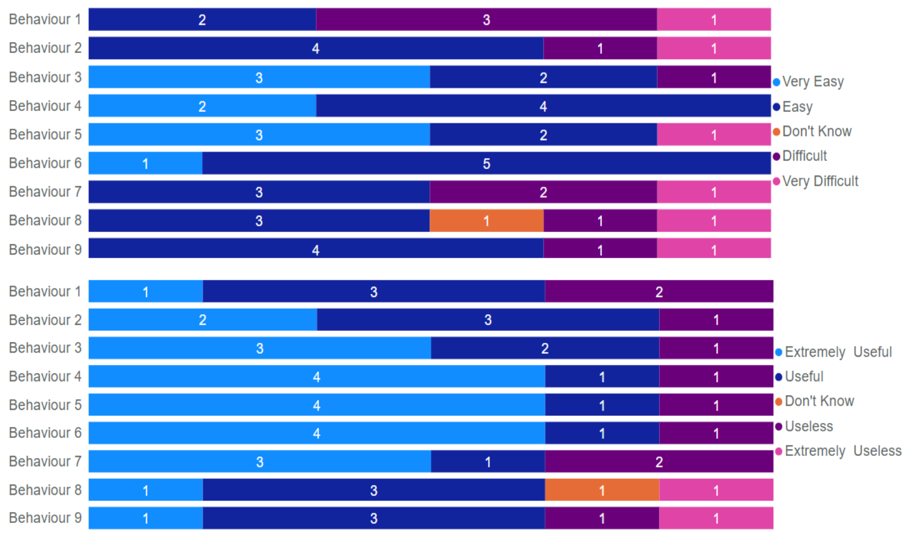

Figure 6.5 Behaviour survey results - Shifting Category.

Figure 6.5 above clearly illustrates that most of the participants in some cases 3 out of 6 participants or more consider almost all behaviors in the shifting category either very easy or easy to adopt except behavior 1 (playing PlayStation during the day instead of night). Since behavior 1 involves kids that's why it might have been perceived difficult to adopt.

On the other hand, if I look the same graph highlighting the perceived usefulness or uselessness part, it depicts and almost similar story, because most of the participants in some cases 3 out of 6 participants or more consider almost all behaviors in the shifting category either extremely useful or useful to adopt. However, behaviour 8 (Turn of freezers during the night to have them on during the day) has one don't know, and one extremely useless rating maybe that's because participant thinks freezers don't consume a lot of electricity and if I look at the pre-knowledge survey results (Figure 6.1) participants have under-estimated the electricity usage of Freezer.

6.2.2 Replacing Behaviors

Figure 6.6 presents the results obtained for the replacing behaviours category. The graph refers the perceived easiness or difficulty as well as perceived usefulness or uselessness of adopting such behaviours. Results are pretty much telling the same story for replacing category just like shifting category behaviors, I could clearly see that most of the participants in some cases 3 out of 6 participants or more consider almost all behaviors in the replacing category either very easy or easy, and extremely useful or useful to adopt behaviors in this category of behaviors. However, behaviour 2 (preparing less energy intensive meal or with a slow cooker, and behaviour 7 (using public transport once a week while the EV is charging) (see Figure 6.6) has shown contrasting results to majority of responses. If I look at behaviour 7 and 2, majority of participants perceive very difficult or difficult in engaging in these (02) sustainable electricity use behaviours 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 sleeping or to watch their consumption every hour, hence they are not ready when it comes to comprising their comfort over a small saving at the end of the month.

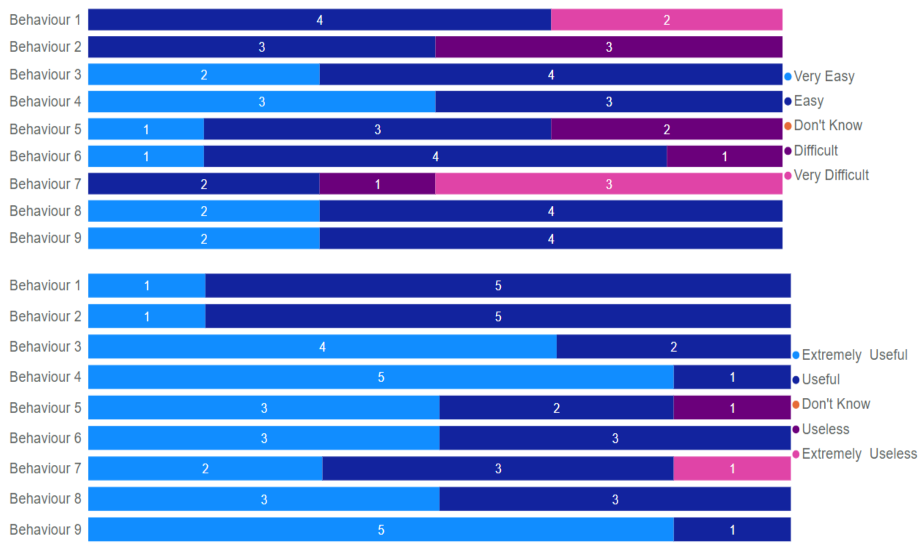

Figure 6.6 Behaviour survey results - Replacing Category

6.2.3 Discussion

The responses from the behaviour questionnaire in both categories of sustainable electricity use behaviours (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, 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, behaviour 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 knowledge survey results (Figure 6.1), in which participants have under-estimated the electricity usage of Freezer.

The replacing category has also illustrated some interesting variations. For instance, behaviour 2 (preparing less energy intensive meal or with a slow cooker, and behaviour 7 (using public transport once a week while the EV is charging) (see Figure 6.6) has shown contrasting results to majority of responses. If I look at behaviour 7 and 2, the majority of participants perceive very difficult or difficult in engaging in these behaviours 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.

6.3 Electricity Consumption Data

In this section, I have analysed the aggregated energy consumption and solar PV production patterns of our experimental group as well as our control group to answer our research question. Furthermore, I also look at the individual appliance consumption data to supplement our findings.

6.3.1 Aggregated Electricity Consumption and PV Production

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.

Ultimately, the comparison of aggregated energy consumption and solar PV production data of our participants helped us unravel to what extent the independent variable (i.e. appliance level electricity information feedback) managed to manipulate the dependent variable (i.e. reduction of electricity usage or electricity bills or consuming more from PV production).

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.

While self-consumption, and excess solar PV gave us information about photovoltaic proliferation, I needed some metric like total energy consumption to assess if participants with the help of feedback were able to curtail overall energy consumption by making better informed electricity use decisions that got nothing to do with photovoltaic proliferation. Thus, total energy consumption before and after the feedback would be used as a metric to analyse their performance after getting the appliance level electricity use feedback.

For the purpose of this analysis, mostly the monthly averages have been considered. In some cases the weekly data have also been looked into, to answer questions raised in the monthly data analysis (e.g., significant increase/decreases in energy consumption) to understand the context behind significant changes in the monthly energy consumption patterns.

6.3.1.1 Experimental Group

Figure 6.7 illustrate the percent change in aggregated energy consumption of participant A with reference to average of aggregated energy consumption (Jan 2019 – September 2019). When it comes to monthly aggregated energy consumption of Participant A, they don't have a lot of monthly energy consumption. It's important to know because when energy consumption is less, then even slight changes like few kWh's can boast significant percent changes Figure 6.7.

If I look at the Figure 6.7, red colour columns indicate after feedback data elements and blue colour columns indicate the before feedback data elements. Participant A energy consumption patterns have been more or less similar usually consumption varying in the range of 250 -300 (kWh) per month.

Let's start with reductions Figure 6.7 shows significant reductions around 17% in the month of May 2019. Still this happens mainly because of a missing data problem, as almost 17% of the data samples were reported missing due to some technical problems. August 2019 also showed some reduction in energy consumption around 8%.

Through our interview with Participant A, I came to know that the reason for that consumption reduction in the month of August 2019 was not related to adopting some best practices using feedback, but due to the family absence from the home for few weeks due to summer vacations.

Some increase in energy consumption can also be observed in Figure 6.7 for the months of June, July and September 2019. But as discussed above, given that, it's a low consumption case few additional kWh's can show significant changes in percent in the graph. Important to mention that few additional kWh's could also have come from our energy monitoring infrastructure as every plug attached to an appliance consumes 1 Watt and raspberry pi (gateway for collecting data) consumes 4 Watts. Also the participant has two sons who were on holidays during this period, thus spending more time at home eventually increasing energy consumption.

Now looking at self-consumption, and excess solar PV for Participant A (Figure 6.8) I could see that they have negligible excess solar PV energy because of their smaller PV production capacity. As such, there is very little margin to explore the value production with individual appliance consumption data with respect to increasing the self-consumption.

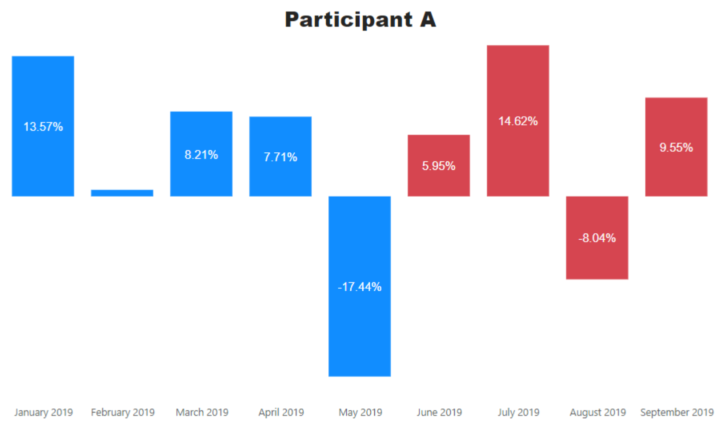

Figure 6.7 Electricity consumption data - Participant A

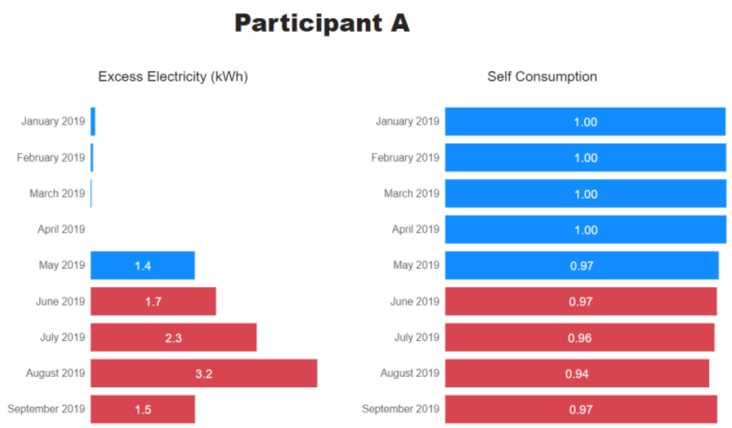

Figure 6.8 Electricity consumption and solar PV generation data - Participant A

Now moving to Participant B, Figure 6.9 illustrate the percent change in aggregated energy consumption with reference to the average of aggregated energy consumption (Jan 2019 – September 2019).

Let's start with reductions first, Figure 6.9 shows that only the month of September 2019 has seen some reduction. The reduction in September 2019 was a bit unexpected based on the previous energy consumption patterns, thus I felt the need to look at the weekly data to understand more about the situation. I found from the weekly data (Figure 6.11) that the week of September 16, marked red in the graph, had significantly lower consumption comparative to other weeks of the month.

Through our interview with Participant B, I came to know that the reason for that consumption reduction in the week of September 16 was not related to adopting some best practices using feedback, but due to the family absence in the home for few days due to summer vacations.

There is also another interesting aspect which deserves mention about Participant B. This participant owns a solar PV recovery system that was installed for effective exploitation of PV production. Whenever the system detects that loads of the house are not enough to exploit the PV production, this solar PV recovery system is activated to ensure that that excess solar PV is not injected in the grid for free rather utilized for heating the water.

Now looking at self-consumption, and excess solar PV for Participant B (Figure 6.10) I could see that they have negligible excess solar PV energy because of the small size of the PV installation, but also due to the presence of the recovery system. The exception again is the month of September 2019 due to the week of absence from the house. Furthermore, during the interview I was informed by the participant that for safety reasons the recovery system was disconnected during that week. Hence the considerable increase in the of solar PV production injected in the grid (i.e., excess electricity).

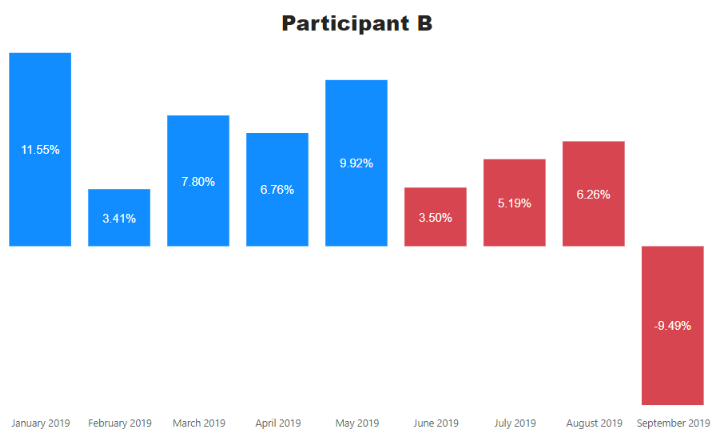

Figure 6.9 Electricity consumption data - Participant B

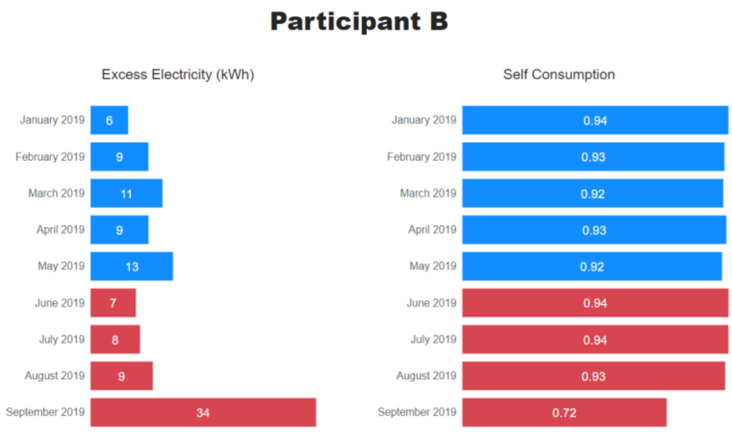

Figure 6.10 Electricity consumption and solar PV generation data - Participant B

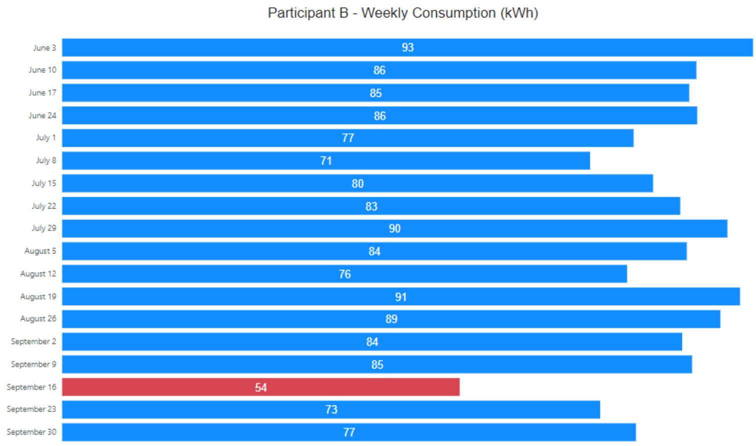

Figure 6.11 Weekly Electricity consumption data - Participant B

Now moving to Participant C, Figure 6.12 illustrates the percent change in aggregated energy consumption with reference to the average of aggregated energy consumption (Jan 2019 – September 2019).

Starting with reductions, Figure 6.12 shows that the month of August 2019 has seen significant reduction which was a bit unusual based on previous energy consumption patterns. Thus I felt the need to look at the weekly data to understand more about the situation. I found from the weekly data (Figure 6.14) that all weeks during the month of August 2019, marked red in the graph had significantly lower consumption comparative to other weeks of the month.

Through our interview with Participant C, I came to know that the reason for that consumption reduction in all the weeks of August 2019 was not related to adopting some best practices using feedback, but once again due to the family absence in the home for most of the time due to summer vacations resulting in very little activity.

Some increase in energy consumption have been depicted in the Figure 6.12 for the month of September 2019. But as understood from the interviews, the increase in the consumption is very likely to be related with the presence of one additional resident in the house (daughter).

Now looking at self-consumption, and excess solar PV for Participant C (Figure 6.13) I could see that they some excess solar PV energy which they don't seem to exploiting it hence eliciting lower values of self-consumption. When asked about this during the interviews, they said that they are aware of this excess solar PV energy thanks to the feedback platform, but they have established very strong routines making it very hard for them to switch to more sustainable electricity use practices to effectively exploit photovoltaic potential. For example, in this household the clothes washer is always turned on around 7AM, when there is very little solar, to make sure that the clothes are washed when the house keeper arrives around 10AM.

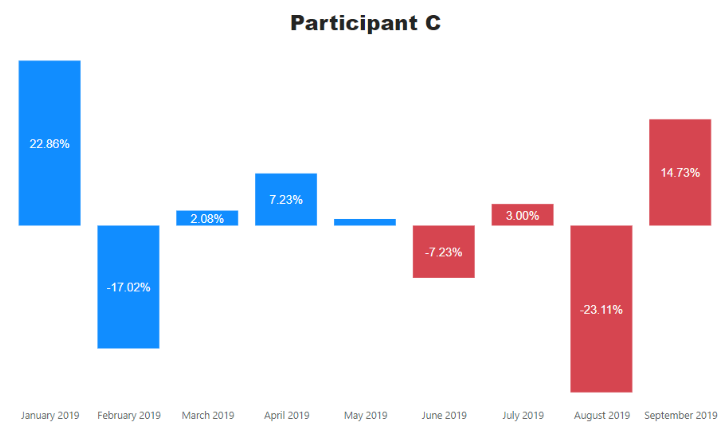

Figure 6.12 Electricity consumption data - Participant C

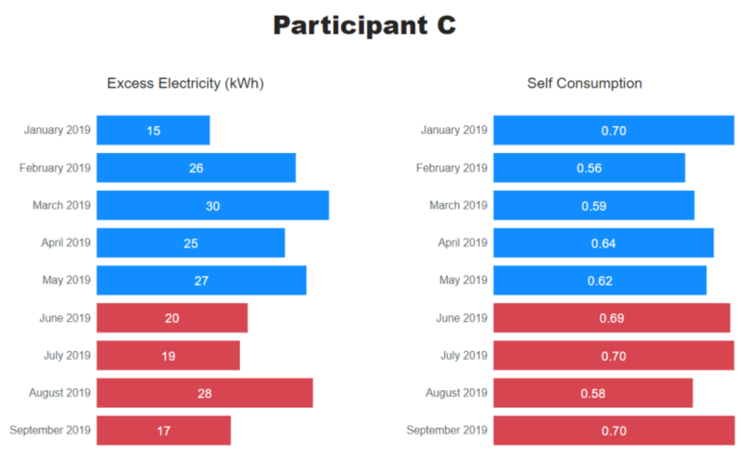

Figure 6.13 Electricity consumption and solar PV generation data - Participant C

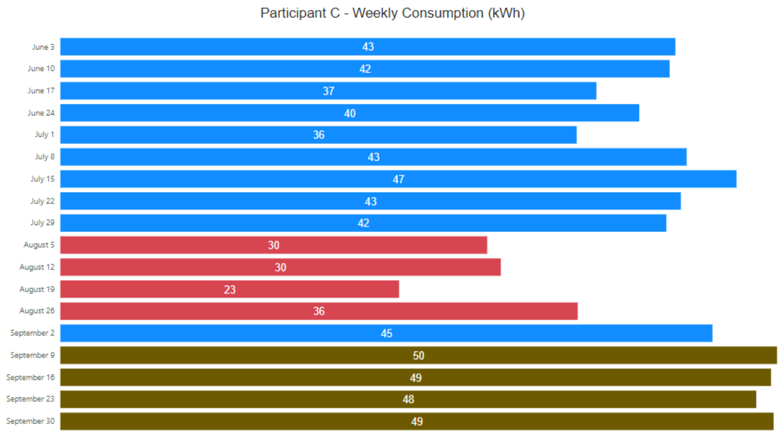

Figure 6.14 Weekly Electricity consumption data - Participant C

Now moving to Participant D, Figure 6.15 illustrates the percent change in aggregated energy consumption of this participant with reference to average of aggregated energy consumption (Jan 2019 – September 2019).

Let's start with reductions, (Figure 6.15) shows that the month of July, August, and September 2019 has seen significant reductions which was a bit unusual based on previous energy consumption patterns that's why I felt the need to look at the weekly data to understand more about the situation. I found from the weekly data (Figure 6.17) that all weeks during these months, marked red in the graph, had significant missing date problems. For instance, the first 3 weeks of July, last 2 weeks of August, and 1st week of September suffer from severe missing data problems.

The main reason for the severe magnitude of the missing data problem is because the owner of this installation changed the entire solar PV facility in June and did not inform the research team. Thus, it was not possible to timely integrate the new changes into our energy monitoring solution. I was also informed that in June he also installed 16 kWh of lead-acid battery energy storage system (BESS). In this case, we are clearly in the presence of an early adopted of this type of technologies, which makes it very hard to reach any meaningful conclusions.

Now looking at self-consumption, and excess solar PV for Participant D (Figure 6.16) I could see that they had some excess solar PV energy during the month of June 2019 which significantly diminished afterwards. The reason for this is the installation of the BESS that not only stores excess production, but also curtails the solar PV production when the full capacity is reached.

During the interviews, the two householders mentioned that they are now more aware of the self-consumption topic thanks to the feedback platform. Furthermore, the wife is usually at home, she keeps checking for the opportunities to have more self-consumption. Therefore, I decided to look into their individual appliances consumption data to see if they have really managed to shift loads during sunny hours to have more self-consumption.

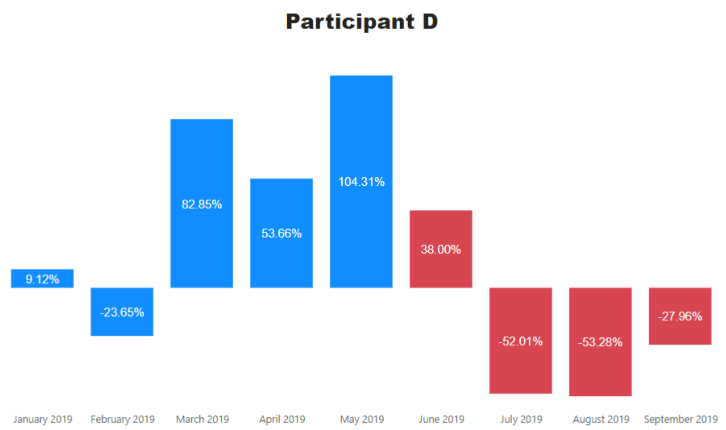

Figure 6.15 Electricity consumption data - Participant D

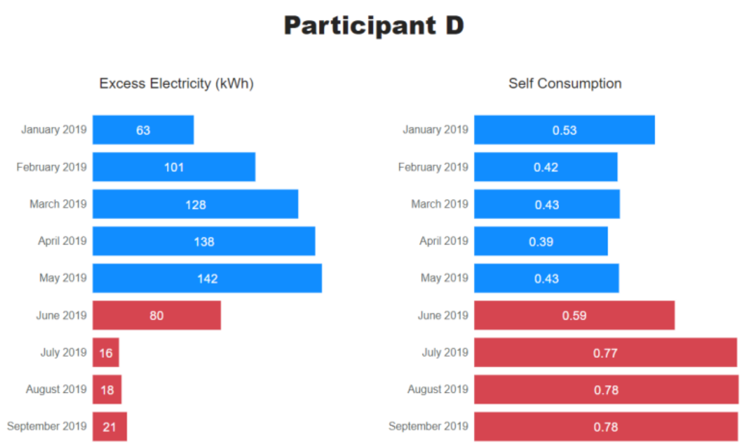

Figure 6.16 Electricity consumption and solar PV generation data - Participant D

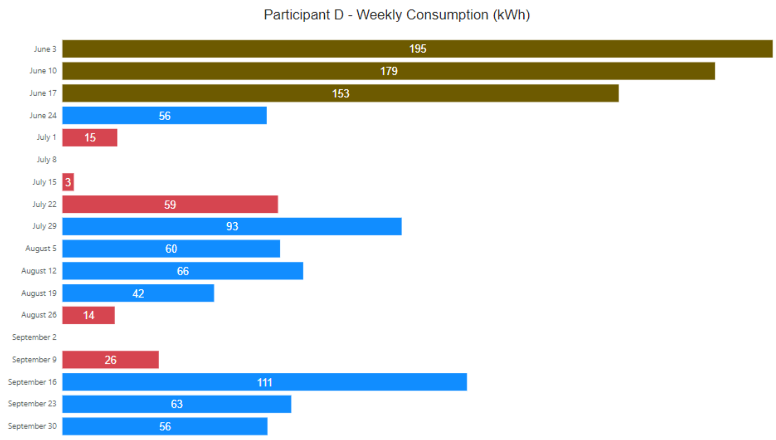

Figure 6.17 Weekly Electricity consumption data - Participant D

Now moving to Participant E, (Figure 6.18) illustrate the percent change in aggregated energy consumption of participant E with reference to average of aggregated energy consumption (Jan 2019 – September 2019).

Let's start with reductions, (Figure 6.18) shows that the month of September 2019 has seen significant reduction which was a bit unusual based on previous energy consumption patterns that's why I felt the need to look at the weekly data to understand more about the situation. I found from the weekly data (Figure 6.20) that all weeks during the month of September 2019, marked red in the graph, had zero consumption comparative to other weeks of the month. The reason for this situation was a technical failure in the gateway responsible for puling and uploading the measurement from the consumption smart-meter. To state more concretely, in this installation there were two gateways, one for collecting aggregate energy consumption data, and another for collecting solar PV production data. Because the one responsible for aggregate energy consumption stopped working, all the solar PV production was considered excess during those days (Figure 6.20).

However, a significant increase in energy consumption have been reported in the Figure 6.18 for the months of June, July and August 2019. Through our interview with Participant E, I came to know that the reason for that consumption increase in the months of June, July and August 2019 was the acquisition of additional refrigeration units. In fact, participant E runs a refrigeration business, which also helps explain the much higher baseline consumption when compared to the remaining five participants.

Furthermore, he said that he knows how to effectively exploit solar PV production but doesn't have lot of flexibility (i.e., excess solar PV energy) (Figure 6.19). Thus, he is planning to increase his solar PV capacity. He also mentioned that he has lots of refrigerators, he is considering deploying sockets with timers in all the refrigerators to turn them off during the night when temperatures are naturally lower and turn them during the day, thus making the most of the solar PV installation. The interesting observation is that when I asked the participant E about perceived easiness and usefulness of adopting one of the behaviours in the behaviours questionnaire (Turn of freezers during the night to have them on during the day), the participant selected the option "don't know". Ultimately, this is a good indicator that before the feedback this was something that he did not consider as an option, possibly for not having a clear picture of the working mode of the refrigeration units.

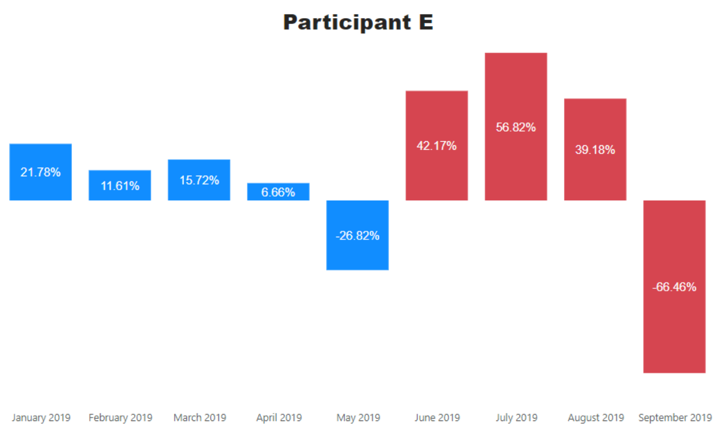

Figure 6.18 Electricity consumption data - Participant E

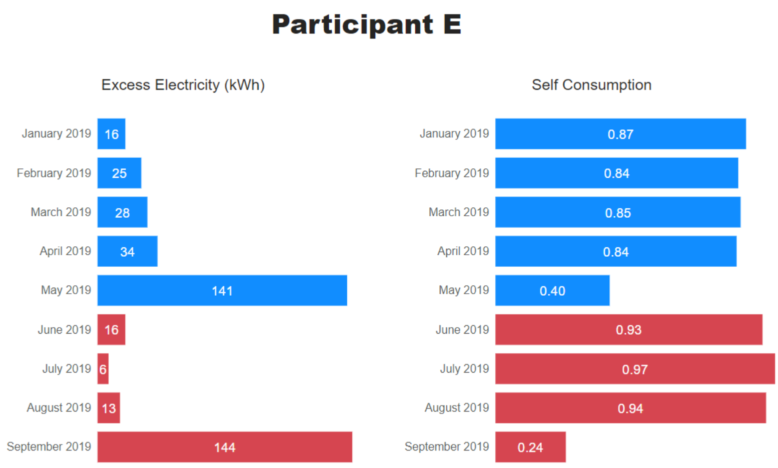

Figure 6.19 Electricity consumption and solar PV generation data - Participant E

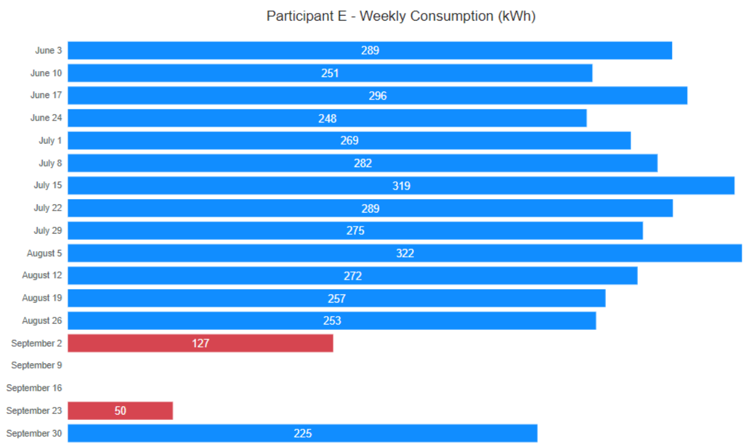

Figure 6.20 Weekly Electricity consumption data - Participant E

Now moving to Participant F, (Figure 6.21) illustrate the percent change in aggregated energy consumption of participant F with reference to average of aggregated energy consumption (Jan 2019 – September 2019).

Let's start with reductions first, (Figure 6.21) shows that some consumption reductions have reported in all the months after the availability of feedback in June 2019.

Through our interview with Participant F, I asked them what they had done differently than previous months before the feedback to unearth the reason behind reductions in the monthly energy consumption after the accessibility of the appliance level use feedback. The surprising thing is that they knew that their energy consumption has lowered in the months after the feedback but couldn't provide a clear explanation for that reduction. Instead, they said that they have tried to consume less electricity. Maybe that's because they came to know about their decrease in energy consumption through their energy bills and didn’t use the system at all or maybe these reductions are due to the Hawthorne Effect explained in details in the chapter Theoretical Framework, this is a kind of bias where participants tend to reduce electricity consumption because they know they are part of some electricity reduction study.

Now looking at self-consumption, and excess solar PV for Participant F (Figure 6.22) I could see that their excess solar PV energy is continuously increasing starting from June till September 2019 that could be because their overall aggregate energy consumption is going down as well and they don’t need a lot of energy. But the graph (Figure 6.22) clearly suggest that they haven’t made any effort to exploit the excess energy.

Therefore, I decided to look into their individual appliances consumption data to see how they have managed to decrease the overall consumption of the house without shifting loads and consuming more solar PV energy. They definitely have reduced consumption of certain appliances which would be clearly understood after looking at the appliance level data.

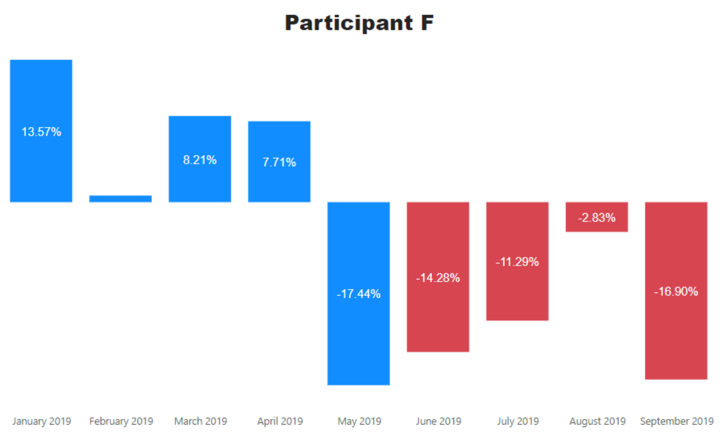

Figure 6.21 Electricity consumption data - Participant F

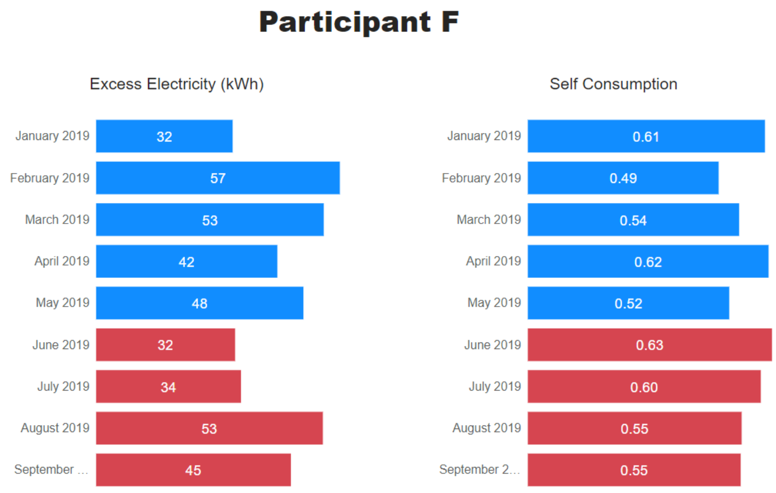

Figure 6.22 Electricity consumption and solar PV generation data - Participant F

6.3.1.2 Control Group

I have also analysed the aggregated energy consumption and solar PV production patterns of our control group just like any other controlled field trial would do to account for the influence of unforeseen external events.

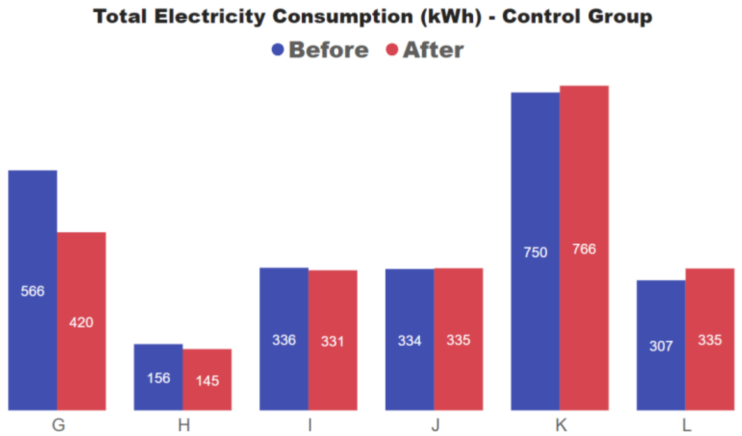

Figure 6.23 Electricity consumption data - Control Group

Figure 6.23 illustrates, for the control group, the average aggregate consumption of four months before (February – May 2019) and after (June – September 2019) the availability of the individual appliance feedback in the experimental group.

It's important to note that they had only access to aggregate energy consumption feedback and didn't have any access to appliance level feedback. As such, similar averages before and after have been plotted for self-consumption (Figure 6.25) and excess solar PV energy (Figure 6.24) for the control group.

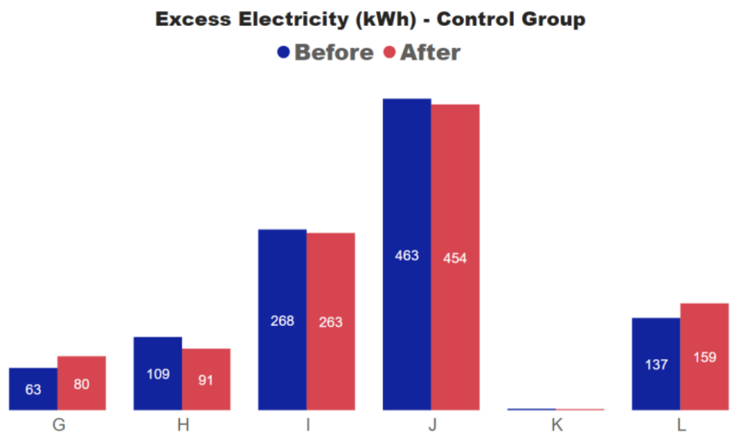

Figure 6.24 Electricity consumption and solar PV generation data - Control Group

If I look at the before and after the averages of control group for self-consumption (Figure 6.25) it's clear that there are no significant variations. Therefore, it rules out the influence of any external event and hence any changes in electricity consumption and solar PV generation data of our experimental group would be most likely due to our intervention strategy.

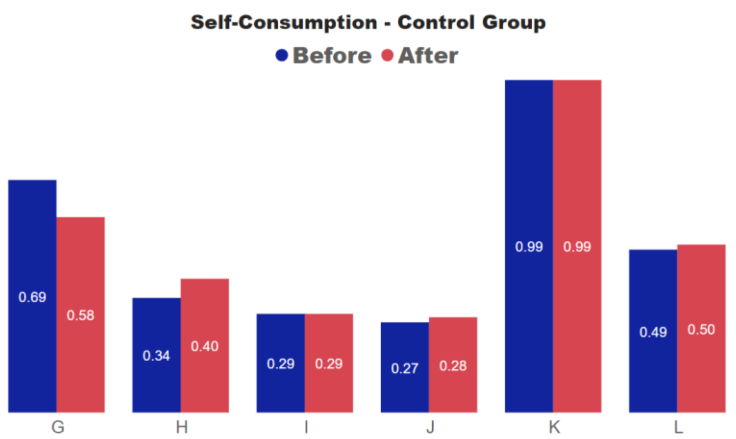

Figure 6.25 Electricity consumption and solar PV generation data - Control Group

6.3.2 Individual Appliance Electricity Consumption

As mentioned above, participant D reported that it is already a common practice to use the clothes washer, dishwasher and iron during the periods with more solar. This in fact can be easily observed by plotting the hourly average consumption of these appliances between June and September (see Figure 6.26). The images clearly show that clothes and dishwashing is done during the day. As for the ironing, it can be seen that between June and August, it can go up to 8PM. Note that in Madeira Island, the sunset only happens after 9PM, meaning that even this late there is still some power being produced by the solar PV system.

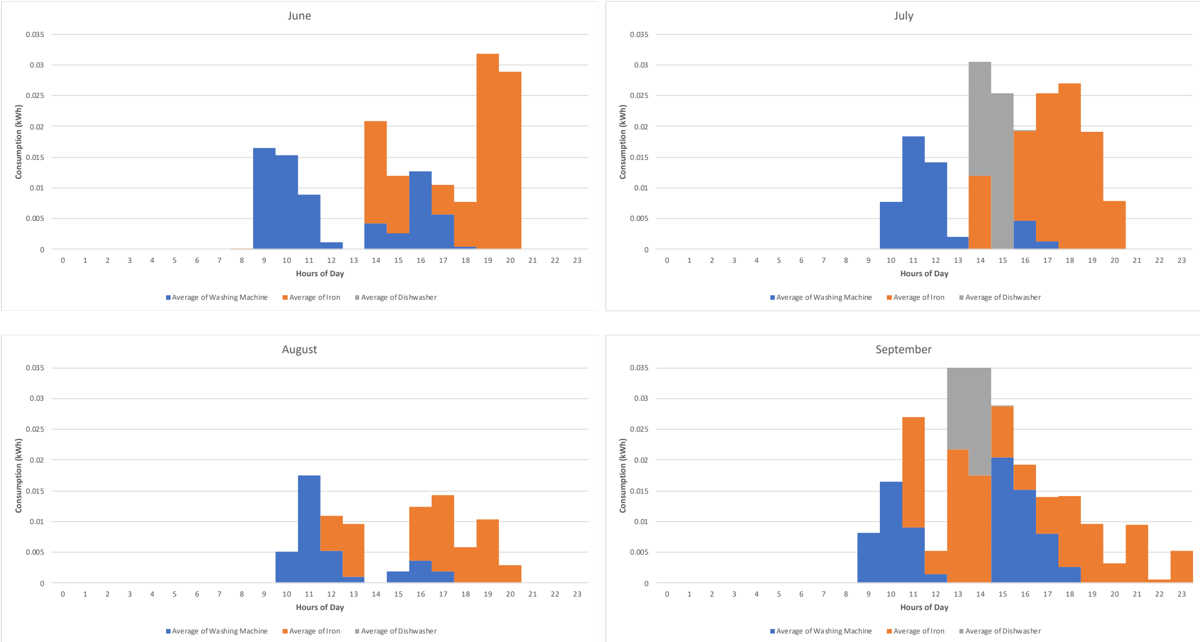

Figure 6.26 Hourly average consumption of the Washing Machine, Dishwasher and Iron from participant D in each month of the study.

In the previous sections it was also mentioned that participant F reported a decrease in consumption during the month of September. In order to further understand how the savings in consumption were possible, in Figure 6.27, I plot the hour consumption of the loads monitored (excluding the fridge).

As it can be observed, there is a very strong routine of appliance usage. Nevertheless, it is evident that during September there is a considerable reduction in the consumption of the Oven (green columns). Likewise, it is also possible to observe a small decrease in the average consumption from the TV (brown columns) and the Washing Machine (dark grey columns).

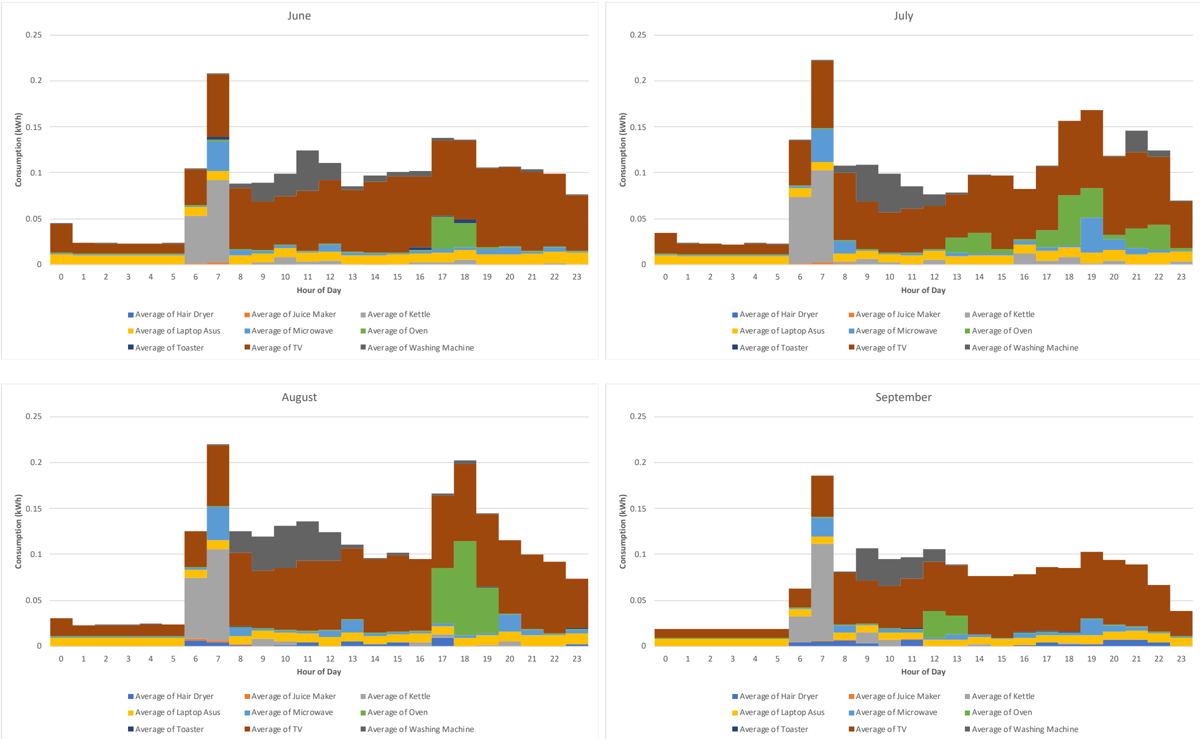

Figure 6.27 Hourly average consumption of the appliances monitored from participant F (excluding the Fridge).

6.3.3 Discussion

After the individual analysis about electricity consumption and solar PV generation data of all the participants in the experimental and controls groups, there is not much left for the discussion.

But if I try to summarize the whole story 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).

Given that the idea of this study is not only about reducing energy consumption of each household, but to have them consume more in periods with excess energy produced. To begin with, 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 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.

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 probably what happened in participant F.

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 and Future Work Directions

In this chapter 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.

7.1 Research Implications

If I 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.

Because 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 because of the availability of appliance level electricity use feedback. 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, I 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.

7.2 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 I had more time then I 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, I 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.

7.3 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).

References

[1] International Renewable Energy Agency (IRENA), *Renewable-Powered Future : Solutions To Integrate*. 2019.

[2] C. Fischer, 'Feedback on household electricity consumption: A tool for saving energy?', *Energy Effic.*, vol. 1, no. 1, pp. 79–104, Jan. 2008.

[3] International Renewable Energy Agency (IRENA), *GLOBAL ENERGY Transformation*. 2018.

[4] G. T. Gardner and P. C. Stern, 'The short list: The most effective actions households can take to curb climate change', *Environ. Sci. Policy Sustain. Dev.*, vol. 9157, no. September-October, pp. 12–25, 2008.

[5] C. Fischer, 'Feedback on household electricity consumption: A tool for saving energy?', *Energy Efficiency*, vol. 1, no. 1, pp. 79–104, 2008.

[6] M. R. Herrmann, 'Smart Energy Feedback in the Home: The Effect of Disaggregation and Visualisation on Householders' Comprehension of Electricity Data (Phd dissertation)', 2018.

[7] S. Z. Attari, G. Gowrisankaran, T. Simpson, and S. M. Marx, 'Does information feedback from in-hom devices reduce electricity use: Evidence from a field experiment', *Nber Work. Pap. Ser.*, vol. 20809, pp. 1–43, 2014.

[8] J. Kelly and W. Knottenbelt, 'Does disaggregated electricity feedback reduce domestic electricity consumption? A systematic review of the literature', 2016.

[9] S. Z. Attari, 'Misperceived energy use and savings', *Nat. Energy*, vol. 3, no. 12, pp. 1029–1030, 2018.

[10] S. Z. Attari and D. Rajagopal, 'Enabling energy conservation through effective decision aids', *J. Sustain. Educ.*, vol. 8, no. January, 2015.

[11] C. Fischer, 'Influencing Electricity Consumption via Consumer Feedback. A Review of Experience', *ECEEE 2007 Summer Study 2007*, 2007.

[12] W. Kempton, C. K. Harris, J. G. Keith, and J. S. Weihl, 'Chapter 6: Do Consumers Know "What Works" in Energy Conservation?', *Marriage Fam. Rev.*, vol. 9, no. 1–2, pp. 115–133, 2005.

[13] P. C. Stern, 'STERN_1992_Energy Conservation_Psychology', vol. 47, no. 10, 1992.

[14] K. Carrie Armel, A. Gupta, G. Shrimali, and A. Albert, 'Is disaggregation the holy grail of energy efficiency? The case of electricity', *Energy Policy*, vol. 52, pp. 213–234, 2013.

[15] T. Wu and M. Srivastava, 'Low-cost appliance state sensing for energy disaggregation', *BuildSys 2012 - Proc. 4th ACM Work. Embed. Syst. Energy Effic. Build.*, pp. 53–55, 2012.

[16] M. Zeifman and K. Roth, 'Nonintrusive appliance load monitoring: Review and outlook', *IEEE Trans. Consum. Electron.*, vol. 57, no. 1, pp. 76–84, 2011.

[17] Bidgely, 'True disaggregation: What it is and why it matters', 2016.

[18] Bidgely, 'White Paper: Impact of Energy Disaggregation on Consumer Behavior - Bidgely', 2014.

[19] G. W. Hart, 'Nonintrusive Appliance Load Monitoring', *Proc. IEEE*, vol. 80, no. 12, pp. 1870–1891, 1992.

[20] N. Panten, E. Abele, and S. Schweig, 'A Power Disaggregation Approach for Fine-grained Machine Energy Monitoring by System Identification', *Procedia CIRP*, vol. 48, pp. 325–330, 2016.

[21] A. Zoha, A. Gluhak, M. A. Imran, and S. Rajasegarar, 'Non-intrusive Load Monitoring approaches for disaggregated energy sensing: A survey', *Sensors (Switzerland)*, vol. 12, no. 12, pp. 16838–16866, 2012.

[22] A. Faustine, N. H. Mvungi, S. Kaijage, and K. Michael, 'A Survey on Non-Intrusive Load Monitoring Methodies and Techniques for Energy Disaggregation Problem', 2017.

[23] A. L. Davis, T. Krishnamurti, B. Fischhoff, and W. Bruine de Bruin, 'Setting a standard for electricity pilot studies', *Energy Policy*, vol. 62, pp. 401–409, 2013.

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

[25] L. T. McCalley, 'Energy Conservation through Product Integrated Feedback', *J. Exp. Zool.*, vol. 78, no. 1, pp. 101–115, 1938.

[26] I. Vassileva, M. Odlare, F. Wallin, and E. Dahlquist, 'The impact of consumers' feedback preferences on domestic electricity consumption', *Appl. Energy*, vol. 93, pp. 575–582, 2012.

[27] I. Vassileva, F. Wallin, and E. Dahlquist, 'Understanding energy consumption behavior for future demand response strategy development', *Energy*, vol. 46, no. 1, pp. 94–100, 2012.

[28] C. of M. V. Home Energy Analytics, Acterra, 'Energy Upgrade Mountain View', no. January, 2015.

[29] H. E. Analytics, 'Home energy disaggregation utilizing smart meter data', *Home Energy Anal. (HEA), Tech. Rep., 2012.*, 2012.

[30] D. Schwartz, B. Fischhoff, T. Krishnamurti, and F. Sowell, 'The Hawthorne effect and energy awareness', *Proc. Natl. Acad. Sci. U. S. A.*, vol. 110, no. 38, pp. 15242–15246, 2013.

[31] G. Wood and M. Newborough, 'Dynamic energy-consumption indicators for domestic appliances: Environment, behaviour and design', *Energy Build.*, vol. 35, no. 8, pp. 821–841, 2003.

[32] J. Bourgeois, J. Van Der Linden, G. Kortuem, B. A. Price, and C. Rimmer, 'Conversations with my washing machine: An in-the-wild study of demand shifting with self-generated energy', *UbiComp 2014 - Proc. 2014 ACM Int. Jt. Conf. Pervasive Ubiquitous Comput.*,

pp. 459–470, 2014.

[33] M. Hansen and B. Hauge, ‘Prosumers and smart grid technologies in Denmark: developing user competences in smart grid households’, *Energy Effic.*, vol. 10, no. 5, pp. 1215–1234, 2017.

[34] Y. Parag, ‘Beyond energy efficiency : A “ prosumer market ” as an integrated platform for consumer engagement with the energy system’, *ECEEE Summer Study Proc.*, no. JUNE 2015, pp. 15–23, 2015.

[35] W. Abrahamse, L. Steg, C. Vlek, and T. Rothengatter, ‘A review of intervention studies aimed at household energy conservation’, *J. Environ. Psychol.*, vol. 25, no. 3, pp. 273–291, 2005.

[36] W. Abrahamse, L. Steg, C. Vlek, and T. Rothengatter, ‘The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents’, *J. Environ. Psychol.*, vol. 27, no. 4, pp. 265–276, 2007.

[37] Rina Consulting S.p.A., ‘SMart IsLand Energy System - Orkney Deliverable D4.4’, no. 731249, pp. 1–26, 2017.

[38] J. Jantzen and B. Bak-Jensen, ‘Smart Island Energy Systems Deliverable D3.1’, no. 731249, pp. 1–50, 2018.

[39] R. M. ACIF-CCIM, Prsma, EEM, M-ITI, ‘“Madeira Pilot Case Study Specification and Assessment,” EUROPEAN COMMISSION, Funchal, Portugal, Technical report 4.1’, *H2020-LCE-2016-2017*, no. 731249, pp. 1–50.

[40] L. Pereira and J. Cavaleiro, ‘On the Value Proposition of Battery Energy Storage in Self-Consumption Only Scenarios : A Case-Study in Madeira Island’, in *IEEE IECon 2019*, 2019.

[41] M. U. Hashmi, L. Pereira, and A. Busic, ‘Energy storage in Madeira, Portugal: co-optimizing for arbitrage, self-sufficiency, peak shaving and energy backup’, pp. 1–6, 2019.

[42] M. Barreto, L. Pereira, and F. Quintal, ‘The acceptance of energy monitoring technologies: The case of local prosumers’, *CEUR Workshop Proc.*, vol. 2382, 2019.

[43] A.-C. Prsma, M-ITI, EEM, ‘Data Collection, Modelling, Simulation and Decision,” EUROPEAN COMMISSION, Funchal, Portugal, Technical report 4.3’, no. 731249, pp. 1–48.

[44] M. U. Hashmi, J. Cavaleiro, L. Pereira, and A. Bušić, ‘Sizing and Profitability of Energy Storage for Prosumers in Madeira, Portugal’, 2019.

[45] A. Bryman, ‘Social Research Methods 4th Edition’, *Oxford Univ. Press*, 2012.

[46] L. Pereira, M. Ribeiro, and N. Nunes, ‘Engineering and deploying a hardware and software platform to collect and label non-intrusive load monitoring datasets’, *5th IFIP Conf. Sustain. Internet ICT Sustain. Sustain. 2017*, no. December, pp. 1–9, 2018.

[47] G. Fitzpatrick and G. Smith, ‘Technology-enabled feedback on domestic energy consumption: Articulating a set of design concerns’, *IEEE Pervasive Comput.*, vol. 8, no.

1, pp. 37–44, 2009.

[48] D. Vine, L. Buys, and P. Morris, 'The Effectiveness of Energy Feedback for Conservation and Peak Demand: A Literature Review', *Open J. Energy Effic.*, 2013.

[49] J. Froehlich, L. Findlater, J. Landay, and C. Science, 'The Design of Eco-Feedback Technology', pp. 1999–2008, 2010.

[50] G. Jacucci *et al.*, 'Designing effective feedback of electricity consumption for mobile user interfaces', *PsychNology J.*, 2009.

[51] Q. Yu, 'Design , Implementation , and Evaluation of a Blockchain-enabled Multi-Energy Transaction System for District Energy Systems', p. 101, 2018.

[52] E. Costanza, S. D. Ramchurn, and N. R. Jennings, 'Understanding domestic energy consumption through interactive visualisation: A field study', *UbiComp'12 - Proc. 2012 ACM Conf. Ubiquitous Comput.*, pp. 216–225, 2012.

[53] M. Ekşioğlu, E. Kiriş, T. Çakir, M. Güvendik, E. D. Koyutürk, and M. Yilmaz, 'Design, User Experience, and Usability. Web, Mobile, and Product Design', *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 8015, no. PART 4, pp. 173–182, 2013.

[54] L. Pereira and Y. Chisik, 'A mouse over a hotspot survey: An exploration of perceptions of electricity consumption and patterns of indecision', *5th IFIP Conf. Sustain. Internet ICT Sustain. Sustain. 2017*, pp. 1–4, 2018.

Appendix A – Behaviours Questionnaire Template

Shifting Category of Behaviours

For each of the questions below, select the response that best characterizes how you feel about the statement, where 1 = Very Difficult, 2 = Difficult, 3 = Don't know, 4 = Easy, 5 = Very Easy.

Type of Behaviors	**Very Difficult**	**Difficult**	**Don't know**	**Easy**	**Very Easy**
Playing playstation during the day	1	2	3	4	5
Cooking dinner earlier	1	2	3	4	5
Using dishwasher for doing dishes during the day	1	2	3	4	5
Doing laundry during the day (both washing and drying)	1	2	3	4	5
Using iron for pressing clothes during the day	1	2	3	4	5
Using a vacuum cleaner for cleaning house during the day	1	2	3	4	5
Charging EV during the day	1	2	3	4	5
Turn of freezers during the night to have them on during the day	1	2	3	4	5
Whenever possible take showers during the day (this implies an electric water heater or a thermo accumulator	1	2	3	4	5

Shifting Category of Behaviours

For each of the questions below, select the response that best characterizes how you feel about the statement, where 1 = Extremely Useless, 2 = Useless, 3 = Don't know, 4 = Useful, 5 = Extremely Useful

Type of Behaviors	Extremely Useless	Useless	Don't know	Useful	Extremely Useful
Playing playstation during the day	1	2	3	4	5
Cooking dinner earlier	1	2	3	4	5
Using dishwasher for doing dishes during the day	1	2	3	4	5
Doing laundry during the day (both washing and drying)	1	2	3	4	5
Using iron for pressing clothes during the day	1	2	3	4	5
Using a vacuum cleaner for cleaning house during the day	1	2	3	4	5
Charging EV during the day	1	2	3	4	5
Turn of freezers during the night to have them on during the day	1	2	3	4	5
Whenever possible take showers during the day (this implies an electric water heater or a thermo accumulator	1	2	3	4	5

Replacing Category of Behaviours

For each of the questions below, select the response that best characterizes how you feel about the statement, where 1 = Very Difficult, 2 = Difficult, 3 = Don't know, 4 = Easy, 5 = Very Easy.

Type of Behaviors	Very Difficult	Difficult	Don't know	Easy	Very Easy
Playing board games instead of playstation at night	1	2	3	4	5
Preparing less energy intensive meal or with a slow cooker	1	2	3	4	5
Doing dishes by hand if at night	1	2	3	4	5
Postpone laundry until full loads available	1	2	3	4	5
Postpone ironing until full loads available	1	2	3	4	5
Don't use a vacuum cleaner	1	2	3	4	5
Using public transport once a week while the EV is charging	1	2	3	4	5
Avoid unnecessary opening of the freezer doors	1	2	3	4	5
Take a shorter shower instead	1	2	3	4	5

Replacing Category of Behaviours

For each of the questions below, select the response that best characterizes how you feel about the statement, where 1 = Extremely Useless, 2 = Useless, 3 = Don't know, 4 = Useful, 5 = Extremely Useful

Type of Behaviors	**Extremely Useless**	**Useless**	**Don't know**	**Useful**	**Extremely Useful**
Playing board games instead of playstation at night	1	2	3	4	5
Preparing less energy intensive meal or with a slow cooker	1	2	3	4	5
Doing dishes by hand if at night	1	2	3	4	5
Postpone laundry until full loads available	1	2	3	4	5
Postpone ironing until full loads available	1	2	3	4	5
Don't use a vacuum cleaner	1	2	3	4	5
Using public transport once a week while the EV is charging	1	2	3	4	5
Avoid unnecessary opening of the freezer doors	1	2	3	4	5
Take a shorter shower instead	1	2	3	4	5