What-a-Watt: Exploring Electricity Production Literacy Through a Long Term Eco-Feedback Study

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***Abstract*—This paper presents the design, implementation and evaluation of an eco-feedback system capable of providing detailed household consumption information and also real-time production breakdown per energy source. We build on recent studies reporting an increased awareness generated by eco-feedback systems that also integrate micro-production information, taking advantage of a closed grid production network on an island with a high concentration of renewables, we deployed the What-a-Watt system in a building with 9 households for a period of 34 consecutive weeks. Results show that all the participating families have shown increased awareness of the production and distribution of electricity, thus becoming more familiarized with concepts such as the different sources of energy and how their availability relates to external variables such as weather conditions and time of day. Furthermore, our results also show, that the families using our system have managed to reduce their overall consumption. This research is a first attempt to provide more effective eco-feedback systems to consumers by integrating complex Smartgrid information in the feedback.**

Keywords— Eco-feedback; Sustainability; User Interfaces; Prototyping

I. INTRODUCTION

Electricity accounts for 40% of the energy produced in the USA. Residential energy use is responsible for 36% of the usage worldwide and 26% of the energy consumed in Europe [1], [2]. One of the reasons for these statistics is believed to be the increased number of electric appliances, especially smaller appliances (e.g. routers, mobile devices, among others) that can be found in a modern household, and which despite their increased efficiency, are currently responsible for more than 50% of household consumption [3][2]. Considering that estimates point to the fact that dwellers can control up to 50% of the electricity consumption in a building [4], the potential for savings is considerable, in particular because there is evidence that people are in fact concerned about the consequences of their overconsumption.

Yet there are considerable inconsistencies between consumer concerns and their actions and consumption awareness [5]. This has motivated researchers and companies to develop ways of presenting consumers with information about how their daily routines impact their electricity consumption, and how they can change their behavior in order to reduce consumption. This type of technology is commonly called eco-feedback and is defined as technology that provides feedback on individual or group behaviors with the aim of reducing environmental impact [6][4].

With regard to the institutional and governmental side of sustainability endeavors, efforts have been focused around the wider scope of the Smartgrid, with the deployment of the so-called smart-meters, which will give consumers feedback about their energy consumption [6]. Generally the Smartgrid consists of the employment of several technologies with the goal of making the production, distribution and consumption of energy more effective. Predictions indicate that savings in CO_2 emissions between 5% and 16% can be achieved with techniques such as advanced metering, dynamic pricing or automated technologies [7]. As a consequence, even though the Smartgrid development is in its early stages, researchers have already started to consider how consumers might react to the different technologies to be employed, [8] for example, the use of personalized energy tariffs [9].

Nonetheless the transition from the current heavily centralized power grid, where a significant portion of energy is wasted in generation and transportation, to the idealized smart grid with rooftop solar panels, plug-in electric vehicles, small generators and services that aim at individual awareness and empowerment is moving power generation to the edge of the network. This shift is not only changing the electricity business, but also impacting the way individuals perceive electricity, its production and distribution.

This paper presents the design and evaluation of the What-a-Watt eco-feedback system, which exposes consumers to the source of their electricity in real time. With this we envision a future scenario where the source of electricity could be a variable used in the Smartgrid services.

II. RELATED WORK

The literature contains an abundance of design strategies and guidelines to implement eco-feedback systems [1][2][3][4], and of theoretical models that can be used to motivate behavioral change [5]. Overall techniques such as presenting timely feedback and comparisons have been referenced as feedback that consumers understand and like.

An alternative path to motivate consumers to reduce energy use is to establish a connection between consumption and environmental impact. Since the long-term effect of individual daily actions on the environment is hard to trace, current

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approaches show predictions or metaphors of how consumption impacts the environment have been proposed.

A. Electricity production feedback

One way to present consumers with the environmental impact of their consumption is to inform them about the resources used to produce electricity. However linking individual household consumption to the different origins of electricity (e.g. wind, water, oil, and sun) is a difficult task, especially if that information is to be displayed in “close” real-time enabling people to react immediately to ongoing changes in consumption. For this reason, most studies have been limited to micro-generation scenarios, in which producers normally have photovoltaic systems or small windmills that generate electricity, which is either fed into the city grid, or is used for their own domestic consumption.

Several researchers have tested this concept, reporting increased awareness and knowledge about electricity production and consumption [6]. In [7] is proposed that presenting the source of energy might help users to create a better mental model of their consumption. A similar observation was made by Wallenborn et al [8] in a study using energy meters in 21 households. The authors argue that to empower electricity consumers, research efforts should focus on making energy more “precious”, in particular because energy monitors only truly develop awareness in already informed consumers.

Besides the increase in awareness of electricity consumption/production, micro-producers have also referenced awareness of other variables that influence electricity production, for instance weather conditions. In [9] the authors observed that users with solar panels installed in their homes, followed their production closely, monitoring the weather to better understand patterns in the production.

Also in the micro-generation field, Pierce et al [10] developed the Local Energy Indicator prototype, which uses the concept of energy metadata. This concept tries to emphasize the information around the source and location of energy consumed. The authors argue that micro-generation systems could be designed to be desirable not only in helping consumers save money but by appealing to user satisfaction of those consuming their own “home-grown” electricity.

Connecting electricity production and consumption with the goal of fostering increased knowledge and engagement in the consumer can result in consumers changing their routines to consume more in periods where there is a higher availability of renewable energy.

This phenomena could result in a reduction in emissions that has the potential to be greater than the values promoted by eco-feedback devices (5~15%) [11], since production can be shifted to periods where more renewables are available or to periods where the thermal plants work with higher efficiency [12] , this shift is also valued by electricity providers since it often results in higher profits when expensive generators are disabled.

III. MOTIVATION

In this paper we advance this state of the art concept with a novel approach to eco-feedback that connects production and consumption information. Unlike the previous approaches with micro-generation, we extend the concept to a whole-island isolated network with a considerable (30-40%) penetration of renewables. Our deployment occurred in a controlled environment on a medium-sized island with a closed grid of about 270 000 people. This unique setup works as a “large-scale micro-generation” and we provide information about the source of electricity (thermal, wind, solar or hydro) in real time. The local grid is composed of three thermal stations that burn fuel/diesel and waste/biodegradable material; seven wind parks in the mountains; ten hydro stations and approximately 700 small private domestically owned photovoltaic installations that feed energy into the grid.

The goal of this paper is to understand whether the high levels of awareness and concern shown by micro-producers can be brought to regular consumers. With this controlled experiment in a closed network we envisage future scenarios in larger networks where consumers could be presented with new service models for electricity that promote sustainability.

IV. THE WHAT-A-WATT SYSTEM

To explore the connection between production and consumption we designed the What-a-Watt eco-feedback system. We planned to deploy the system for a long period of time and this required the infrastructure to be reliable and robust, as it would need to be used by several families in their normal routines. In this section we describe the design and implementation decisions of our infrastructure, starting from the sensing infrastructure, to the design of our Android client application.

A. Sensing framework

Our sensing and eco-feedback platform is based on a custom made energy monitoring system. Our system is based on a netbook and a bespoke DAQ (Data Acquisition Board) that is installed at the entrance of apartment buildings, hence avoiding the need to install hardware in the monitored houses. The DAQ is responsible for acquiring current and voltage waveforms that are further processed by a netbook running our algorithms and a webserver that provides access to the consumption data through a layer of restful web services. Real time data (consumption and power events) are made available through two sockets using a custom communication protocol.

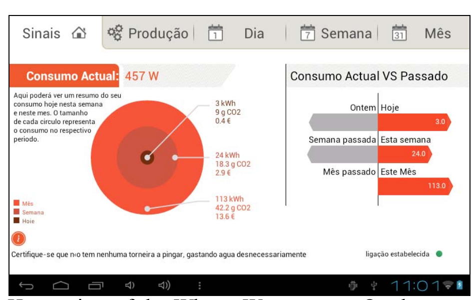

Fig. 1: Home view of the What-a-Watt system. On the top of the screen there are the different tabs used to navigate around the interface.

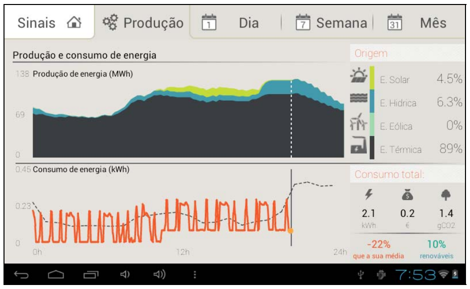

Fig. 2: View of the system with information about the source of electricity. On this particular day there was 10% of renewable energy in the grid, and at that particular moment there was 4.5% solar, 6.3% hydro, 0 % wind, and 89% thermal

B. Electricity production

The electricity production data was obtained through a partnership with the local electricity company responsible for the distribution of the electricity in Madeira island, Portugal. Every 15 minutes the provider places updated quotas for thermal, wind, solar and hydro production under a URL, and a web-service implemented on our server queries that information and inserts it into an online database. Additionally the electricity provider also provides the outcome of a model used to predict production from the different sources of electricity, those values are handled in a similar manner to the production.

C. Ecofeedback

The feedback was given using a 7" android tablet. The system was developed using native development SDK. The Android application is composed of a set of tabs that represent the production information and summary of the consumption on a daily, weekly and monthly basis.

The production view is the default mode of the application and the system reverts to this visualization when no interaction happens for a pre-defined period of time. The application never goes to idle mode as is common with several android applications. The design of the views that represent consumption over the day, week and month are an evolution from a previous version of the system that had already been tested with users in a real world scenario for 17 weeks [17].

1) Consumption feedback

The summary view contains two charts representing the consumption of the current day, week and month, and a comparison between homologous periods. Also on this tab the system presents the user with a "tip of the day" with general sustainable recommendations (see Fig. 1).

The "Day", "Week" and "Month" views contain a chart with the consumption during the selected time period. There is also information about the total aggregated consumption, the peak consumption and how it compares with the baseline for that period.

2) Production feedback

The electricity production visualization is the result of an iterative design process where several prototypes were created and tested with users. This way the selected representation shows a "cumulative" chart representing all the sources of energy used during the day, their quotas relative to each other, and a prediction of which sources would be available for the rest of the day (Fig. 2). For example, at 18:00 the chart displays the quotas of the different sources used so far, and their availability for the rest of the day.

Each source of electricity has a color associated with it: yellow for solar, light blue for hydro, light green for wind, and dark grey for thermal. This view also presents the total percentage of renewables used during the day, and the real time quota of each source. Additionally the production view presents a high-resolution chart of the daily consumption in which the data is grouped in five-minute intervals. Another dotted line chart is superimposed upon this chart, displaying the average consumption for that day of the week (Fig. 2 bottom). This allows users to align their real-time consumption with the different sources available at the time. We were also expecting that the high-resolution chart would allow consumers to identify single appliances, or everyday activities such as cooking lunch or playing a videogame console thus enabling them to extract more information about their consumption data.

D. Collected data

The sensing framework computes consumption at 50 samples per second and stores the average consumption every other minute in the underlying database. These consumption values are used to compute the average per hour used in the analysis and on the different charts of the application. Additionally, if necessary the system accesses higher resolution data (2 consumption points per minute). The system also records all the transitions between the different interface screens, which provide a good metric to understand how the users interact with the system. An interaction with the system was considered every time the user selected one of the different tabs of the interface, or touched one of the buttons.

V. EVALUATION

To evaluate the What-a-What system we selected 9 families from an apartment building corresponding to the average consumption of households in the island's main city which contains more than 50 000 residential consumers. The research team surveyed several buildings, with different demographic and consumption profiles, looking for a building where the residents had similar medium salary incomes and energy consumption profiles. Five families were selected to use the What-a-Watt application (a total of 12 individuals) and four others were used as a control group in which the consumption was measured but no feedback was provided.

We argue that a long-term study is required in order to fully understand whether the awareness shown by micro-producers can be passed to regular consumers. The production of energy is highly conditioned by external phenomena like the weather and daylight. The duration of our deployment guarantees that consumers are exposed to different conditions helping them to assimilate the reasons behind the different quotas presented by the What-a-Watt system.

VI. METHOD

We asked all the families to complete a questionnaire with general information regarding electricity consumption and demographics at the time of recruitment.

The sensing framework was installed and baseline data (without feedback) was collected for a period two weeks. After this period, the five participating families were given a tablet with the What-a-Watt system installed and instructions on how to use the system. With this procedure we guaranteed that all the houses had two weeks of baseline consumption allowing for the individual analysis of each household's data. One week after the system was installed, the research team visited families to clarify any problems they might have had with the system, and to guarantee that everything was working correctly

Nine weeks into the deployment we visited the families and asked them to complete a small questionnaire regarding the use of the feedback system, including the perception of potential savings of electricity. The questionnaire was analyzed in conjunction with the interactions and consumption data. The outcome of this analysis was then used to adapt a structured interview for each family. Interviews with families lasted between 20 and 45 minutes, and were recorded and transcribed to text.

This article presents the findings up until the end of March 2014, corresponding to 32 consecutive weeks (approximately 8 months) of usage of the eco-feedback system (plus two weeks of baseline data).

A. Quantitative assessment

To analyze the family consumption during the study the energy data was grouped by week, since we believe the weekly consumption provides a good metric to group all energy related routines in a household. The only exception is the baseline consumption since we had two weeks of data and therefore used daily consumption to identify trends. Similarly the interaction values are also aggregated by week. See the section, Collected data, for details about the consumption and interaction values stored by the What-a-Watt system. In this section the participating families are referred to as F1, F2, F3, F4 and F5.

1) Electricity consumption

Three different approaches were combined to understand the variations in consumption during the period of the study. Firstly the control group was used to compare the consumption of households using What-a-Watt in houses without any feedback on electricity consumption. Second, the fifteen days of recorded baseline consumption was used to compare the consumption before and after our intervention. Lastly the overall consumption trend was analyzed. One family (F1) had to leave the apartment on the 14th week of the study and the results presented below take that fact into account by removing this house from all the averages after the 14th week. Table 1 displays how the electricity consumption evolved in the three groups (houses that used the What-a-Watt system, control group, and both).We have used the slope of the linear regression fit to the consumption of all the houses to calculate the overall trend in the consumption.

During the 32-week deployment, the group of all houses in the building increased their energy consumption by 14% (see Table 1). Families using the What-a-Watt system decreased their consumption by 18% (Table 1) and houses without any feedback increased their consumption by 41% (Table 1).

More specifically, all the four houses in the control group increased their consumption (+112%, +15%, +7% and +18%). Of the five houses using the What-a-Watt system, four reduced their consumption (-1%, -10%, -1% and -96%) and one household increased consumption (6% increase). The 96% decrease found in the case of F1 can be explained by the family leaving the apartment during the 14th week of the study (however in the analysis we only considered the time period when the family was using the What-a-Watt system).

TABLE I. CONSUMPTION TREND IN THE SELECTED BUILDING.

Table Head	Consumption trend	
	Baseline	***Study***
Building	-8.1%	+14%
Control Group	-16.3%	+42%
Study Group	+21%	-17%

2) Interactions with the What-a-Watt system

On average there were nine interactions per week for each household during the 32 weeks of deployment (sd=30). However the interactions with the system reached a peak in the first four weeks of the study, averaging 52 interactions per household in that period.

This is consistent with previous findings reported in literature (e.g. [13]) which estimate the novelty period for eco-feedback to be, on average, four weeks. After that the interactions with the system decreased to an average of three interactions per week per household. The actual interaction values differed between all households in the study. The most accessed view was the "Home" view of the system, followed by the "Production view" (this pattern was consistent in all the installations). There were no observed patterns regarding the accesses of the feedback system by time of day or day of the week.

B. Qualitative assessment

In this section we analyze the different interviews with family members during and after using the What-a-Watt system. After transcribing the interviews we organized users answers into topics that grouped their impressions about the eco-feedback device. Our analysis disclosed the following two topics: Awareness of the electricity consumption and Electricity production.

1) Awareness of electricity consumption

The eco-feedback was well understood and received and none of the families had any problems using the system. The eco-feedback system clearly increased consumer awareness of their electricity usage, this observation was expected (from literature) and it was consistent within all the households. Families stated that the system alerted them to certain behaviors, and also allowed them to follow their energy consumption closely.

Families stated that feedback could be improved by adding features such as a tool to compare consumption with other similar families in the study, as pointed out by F4. It was also mentioned by F2 that it would be interesting to have consumption information by appliance or by room. However families also stated that the high resolution chart in the Production View of the system allowed them to trace individual appliances as the daughter in F2 explains: "there is a peak here during lunch, because today we used the microwave, I am sure it was the microwave, we detected it as soon as it was turned on".

All the families mentioned that they were already concerned about their electricity consumption and sustainability. Actions like changing to low-power light bulbs, buying more efficient appliances or opening the curtains to allow sunlight to get through, were already adopted. However the system allowed them another level of control over their actions by matching their perceptions with actual consumption data. F5 mentioned that the system worked as a reminder, alerting them to perform or do something that they would normally do but sometimes forgot. Another consistent observation across all households was how easily families were able to trace abnormal consumption routines (for example a peak in the daily consumption chart) with certain behaviors. The father from F3 explains how he could see that his son was playing console at lunch time: "we can check that he turned on the consoles and the TV, I bet there is a peak in here, he also open the refrigerator door, yeah we can see it…".

2) Electricity production

All the families saw electricity production information as something new and interesting, although some family members already had a rough idea of the available sources. Everybody learned something from the What-a-Watt system, for example F3: "I knew about the different sources, but I had no idea of their quotas, I thought the solar would be higher that the wind power, I was also expecting more presence of the hydric energy".

Families relate the source of energy to the infrastructure they encounter in their day-to-day lives, for example everyone predicted the presence of wind power in the local grid, since the wind parks in the mountains are a sight that is almost impossible to miss, " wind power yes… I've seen the windmill up there" F4. The same family was not aware that the islands produce electricity from water or sun, " I had no idea about the solar power, or even hydro". Similarly families predicted that the sources that are more "visible" were responsible for a bigger part of the island total quota as the daughter from F2 argues: "We have all those windmills up there… I was expecting that they would be more used... I had no idea it was so little" (referring to a particular day with less than 10% of presence of wind power).

Families expressed concern about the source of the electricity, they were aware that the origin of energy can influence the level of pollution. " of course its something that concerns us… we know that we should use our natural resources correctly ". Being in a closed ecosystem also made families aware of the cost of the energy, not their monthly bill, but the cost for the region since all the energy is produced on the island, as the father from family F3 explains: " Of course if it was all hydro, and wind power it would be ideal… because of the pollution... but also cost for the region it would be much better all wind hydro and solar ".

All families interviewed were surprised to learn that the price of electricity is the same even if it comes from different places. Therefore after becoming familiar with the different sources, family members proposed several approaches to maximize the use of renewable sources. For example the husband from F5 proposes having two prices for non-renewable and renewable: "I don't think it is fair to pay more for an energy that costs less to produce that the other… I would even say that I would prefer to pay a little more for a non-pollutant energy because maybe that way I would be encouraging a stop in the more pollutant energies production".

In general families understood that the investment in renewable energy made by the provider has to be covered by someone, but they found it hard to understand that they were paying more for pollutant energy especially if the renewable presence is significant. As the husband from F5 pointed out " if you tell me that there is 50% thermal and 50% renewable in the grid… in that case it is not fair paying a higher price for a pollutant energy... I would even prefer to pay a little bit more at knowing that my consumption does not have a cost to the environment."

The system allowed participants to relate the energy produced on the island with variables such as weather or time of the day, as the husband from F5 stated: " I have that impression, if there is nice weather the solar energy increases.. if its raining its bad for solar power". This concept was grasped rapidly and some families could even predict the future energy sources available based on the weather forecast, and this could work the other way around, predicting the weather based on the available sources as stated by F4 "Sometimes I checked that there was some wind power, but I didn't notice any wind around here, I'm sure that it was windy in the mountains".

None of the families mentioned changing any routines based on the available energy sources. Their busy day-to-day lives make it harder to plan that way. F4 mentions that: "If I spent more time at home, but I'm only at home after 19:00, and I have to do my stuff around the house, it is complicated to turn on the appliances just because now there is more wind energy". The adjustments in family routines were more likely to be made as a result of the cost of energy, and by the feedback device that made that cost visible than motivated by the source of the electricity, as the mother from F5 mentioned "turning on plugged in devices, and reduce the usage of the microwaves… it was mostly because of the cost". The use of electricity was experienced as something completely opaque from a consumer point of view, as the father from family F3 mentioned, " when we turn something on, we don't even think where does it come from … maybe we should"

VII. Discussion

Our eco-feedback device proved to be an easy tool to understand and incorporate into consumer routines. We argue that the portability of the device itself, together with the overall robustness and reliability of the hardware-software platform allowed us to offer consumers an experience close to the one offered by commercial solutions. This was possible because our research platform had already been tested in other situations and was the result of an iterative development process. The What-a-Watt system helped families to reduce their consumption when compared to the baseline data and the control group. Our results are in line with what literature reports for eco-feedback devices, however we believe it is important to mention that in our studies the consumption tended to decrease during a time of the year when the overall consumption is likely to increase, (Autumn and Winter) as it was confirmed by the increase in consumption in all the control group houses.

Families considered the energy production information as something new and interesting. We argue that our system helped consumers correct several misperceptions about the electric grid making them more knowledgeable about the long-term implications of energy consumption.

Our work argues that the information about the source of the electricity is a valuable addition to eco-feedback devices or even the proposed smart meters. Furthermore we hypothesize that if in a closed system like a small island where the infrastructure used to produce electricity (i.e. windmills, thermal stations or photovoltaic installation) is clearly visible to citizens and these misperceptions still exist, they are likely to be bigger in larger metropolitan areas where the majority of the electricity comes from outside the residential and commercial area of the city.

Regarding our goal of bringing awareness and knowledge of micro-producers to "regular" consumers, we consider that the What-a-Watt system has achieved this goal. Our interviews disclosed that consumers rapidly grasped the basic concepts of the grid, and were aware of how variables such as the weather or time of day affect the electricity distribution. Besides the cost, the source of energy might also be of value for consumers when making decision between tariffs or providers.

Even though all families showed concern and awareness of the source of their electricity, none alluded to making any change in their routines to maximize the usage of a particular energy source. Families mentioned that the lack of time was the biggest hurdle to making an adjustment. In fact our analysis of the routines of the families in the study disclosed that appliance usage is mostly centered around a period of time (evening/night), where for example the presence of solar energy is virtually zero.

VIII. Conclusions and Future Work

In this paper we described What-a-Watt an innovative eco-feedback system integrating both household energy consumption and real-time production breakdown information from the grid. We explored future scenarios where production information could become available to a wider network hopefully leading to better-informed consumers and sustainable scenarios of energy consumption and awareness.

We acknowledge that our sample of 12 individuals does not allow us to generalize our findings. However our results reveal that consumers quickly became aware of the raw energy used to produce their electricity. Furthermore consumers were able to connect variables such as weather and time of the day to the availability of the different electricity sources. Regarding consumption, on average consumers with the What-a-Watt system managed to reduce their energy bill, inverting the tendency to increase consumption as was observed in the control group.

After many years of research it seems clear that eco-feedback is not the "silver bullet" for sustainable energy consumption. Our unique setup is another contribution for future scenarios where energy (or the consequences of excess energy demand) will no longer become sustainable. In such a scenario, energy production could evolve into new service-oriented models where end-users and consumers will have an important role matching consumption patterns with the availability of renewable energy.

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