Handy feedback: Connecting smart meters with mobile phones

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ABSTRACT
Reducing their energy consumption has become an important objective for many people. Consumption transparency and timely feedback are essential to support those who want to adjust their behavior in order to conserve energy. In this work, we propose an interactive system that provides instantaneous feedback concerning the energy usage on household and device level. For that, we used and extended the capabilities of a smart electricity meter, built a web-based API to enable interoperability with other applications, and developed a mobile phone interface that allows users to monitor, control, and measure the consumption of single appliances. Our system illustrates a way how usage barriers can be lowered and how high user involvement can be created. By providing users the electricity feedback needed – in real-time and on device level – the system allows for identifying the biggest energy guzzlers and helps users decrease their energy consumption.

Categories and Subject Descriptors
H.4.m. [**Information systems applications**]: Misc.; H.5.2. [**Information interfaces and presentation**]: User Interfaces.

General Terms
Management, Measurement, Design, Human Factors.

Keywords
Energy use, smart meter, mobile computing, advanced metering, load monitoring, visualization, feedback systems, sustainability.

1. INTRODUCTION
The electricity consumption in residential buildings is highly dependent on the behavior of the habitants. A major burden for people who are willing to save energy at home is the lack of information about their energy consumption. Neither can they easily identify how much electricity their household consumes, nor are they able to compare how their consumption to a typical household of similar type, size, and location. Moreover, as studies have shown, a monthly feedback provided on the energy bill is not sufficient [1, 9]. Thus, it is important to apportion the energy consumption and understand how much energy different appliances consume to enable users to adapt their behavior more efficiently [4]. Currently available off-the-shelf products that depict the energy consumption in near real time, such as smart power outlets, are helpful but do not fully meet the user needs as these devices have a high usage barrier and often require complex installation. Moreover, they lack the ability to easily demonstrate, measure, and compare the energy consumption of single devices. As a result, many users do not take advantage of such existing solutions. In order to raise consumption awareness, prior work [3, 16] indicates that timely consumption feedback and guidance are key to stimulating electricity conservation and enabling users to change their behavior in a way that decreases their power demand. It is generally expected that by providing detailed and immediate feedback between 5% and 15% of the electrical household energy consumption can be saved [4]. These savings result from a change in behavior - that is, using devices (including energy-efficient appliances) less and/or more efficiently.

In this work we propose a system that overcomes the above-mentioned limitations of existing electricity consumption monitoring systems. It offers the possibility to interactively measure devices in the house, it features a low usage barrier, and it can easily be used in everyday life. Since based on a smart electricity meter, which presence will significantly increase in the near future, it is simple to set up and requires no additional hardware installation. Further, our system provides both: real-time feedback on the entire electricity usage and on the consumption of many appliances at device level. As a result, this allows for users to monitor, measure, and compare their energy consumption and efficiency level on household and on device level.

The reminder of this paper is structured as follows. Section 2 reviews relevant work in the field of appliance load monitoring and consumption feedback. Section 3 presents the architecture we developed to acquire and visualize electricity usage. Section 4 describes and evaluates the portable user interface. We conclude this paper with a discussion on future work of the proposed system.

2. RELATED WORK
There exists a number of energy monitoring products and research approaches. In general, they can be divided into solutions that focus on visualizing the entire consumption of the household and into those that provide feedback on device level.

The first category contains numerous commercial solutions. The most promising include Wattson [5], Onzo [11], Power Cost Monitor [2], and TED-1000 [7]. Once installed, they visualize the entire electricity consumption of the household on a central, sometimes portable display. However, since most of the solutions require complex installation either around the electric wiring behind the electricity meter or in the fuse box, many users are discouraged to buy and deploy such systems. In addition, these systems cannot provide feedback on the electricity consumption of single devices. Several other highly promising systems are

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currently under development. Peterson et al. [15] use a circuit breaker box that has to be attached to the fuse box to acquire the electricity data per circuit and, similar to the proposed system in this work, intend to use a mobile phone as user interface (UI). Since the work focuses more on the design aspects, it does not state what feedback times and measurement granularity can be achieved. Yun [19] proposes a similar system that uses a sensor clip attached to the fuse box to measure the entire consumption and provide continuous real-time feedback on a minimal UI. In contrast to our work, these systems are not developed for easy interaction with the user, which we think is essential when it comes to building an appealing energy visualization tool that is used regularly or for a longer period.

In the second category, we classify approaches that provide feedback of the consumption on device level. Commercially available products are mostly smart power outlets, like the Energy Optimizers Ltd.'s Plogg [6], Kill-a-Watt / Tweet-a-Watt [12], and SmartLinc [17]. They aim more at monitoring, controlling, and automating the attached device. Jiang et al. [18] developed a wireless networked sensor node that measures the power consumption at the outlet and uses the communication interface to automatically transmit the data. Paradiso [13] embedded a multimodal sensor network node into a power outlet to monitor the electricity consumption and infer the appliances being used in the house. In general, all approaches require a current sensor to be installed inline with each monitored device. This leads to high adoption barriers. Each time users want to monitor the consumption of a new device, they are forced to plug the device to the smart outlet or deploy multiple sensors throughout the house.

There exist several other interesting approaches that allow for providing device level feedback. For example, Patel et al. [14] developed a system that tries to infer what devices are currently running from the electrical noise on the residential power line. Kim et al. [10] have developed a system that provides fine-grained feedback on the power consumption. For that, they use three different types of passive sensors deployed near devices throughout the household to estimate the electricity consumption. In contrast to these systems, our approach does not require additional sensors and does not make the assumption that devices can be identified by characteristic noise patterns. Instead, it builds on a smart electricity meter which are going to be installed in large numbers in the US and Europe over the next years (as required by law in many countries) and enables users to interactively measure the electricity consumption with a mobile client such as a smartphone.

Our work tries to close the gap between the two existing categories and provide users the form of electricity feedback ideally needed to adopt their behavior accordingly: in real-time and on device level. Since the proposed system is based on a smart electricity meter (the light-weight gateway could later for example be integrated therein), it is simple to install and requires neither modification of the wiring, which in most houses in Europe is difficult to access, nor additional hardware at device level. Through providing a web-based interface to the smart meter, we integrate the physical world into the web and allow for easy interoperability with other applications that can be developed on top of the system. Moreover, through the UI on a mobile phone we achieve both continuous real-time feedback and the possibility to interactively monitor and compare the consumption of devices.

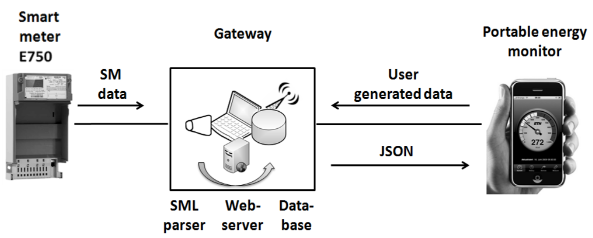


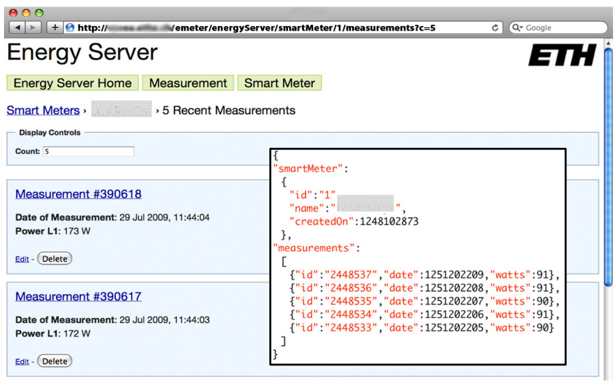
Figure 1. Smart meter communicating with the mobile UI

3. ARCHITECTURE

The architecture of our implemented system is based on three independent components (Fig. 1): a smart electricity meter with the connected devices that are monitored in the household, a gateway that manages and provides access to the data acquired by the smart electricity meter, and the portable UI on a mobile device that allows for real-time feedback on the energy consumption.

The first component, the smart electricity meter provided by Landis + Gyr, measures and logs the energy consumption of the devices that are attached to the electric circuit of the household. In contrast to the classical electricity meters used today, it contains a communication interface that can be polled to acquire the data. In order to provide continuous real time measurements, we extended the meter's capabilities to send out all available data to the network's broadcast address every second.

The second component, the light-weight gateway, is a software module written in Java and connected to the smart electricity meter. It consists of a parser, a data base, and a tiny web server. The gateway manages and handles the captured data. In order to enable interoperability with other applications, such as the developed UI, we additionally embedded a web server that is based on the RECESS![1]-framework. The gateway acquires the logged data from the smart electricity meter on a continuous basis in real time, by triggering the transmission of the captured data and parsing it into the database. The Smart Message Language (SML)[2] parser automatically polls the meter's communication interface and stores the received data in a SQL data base. The web server provides access to the gateway's functionalities and the smart meter's sensor values using URLs. The benefit of making the meter application accessible through a simple web API (similar to a RESTful approach [8]) is the direct integration of the smart electricity meter to the web which eases the development of applications and prototypes on top of the smart electricity meter. In fact, it allows



{
"smartMeter":
{
"id":"1"
"createdOn":1248102873
},
"measurements":
[
{"id":"2448537","date":1251202209,"watts":91},
{"id":"2448536","date":1251202208,"watts":91},
{"id":"2448535","date":1251202207,"watts":90},
{"id":"2448534","date":1251202206,"watts":91},
{"id":"2448533","date":1251202205,"watts":90}
]
}

Figure 2. Screenshot of energy server UI and JSON response

[1] www.recessframework.org

[2] www.t-l-z.org/docs/SML_080711_102_eng.pdf

us to monitor the sensor values and control the gateway components simply by calling the corresponding URL in a web browser. In response to the call, the gateway wraps the results in form of a JSON[3] message. JSON is an alternative to XML often used as data-interexchange format for web mashups. Since JSON is a light-weight format, we believe it is better suited to enable interoperability with devices of limited capabilities.

Figure 2 shows an example of the last five measurements of the currently available monitoring data that can be received and for example displayed in a web browser, as response simply by calling the following URL:

http://[serverAddress]/emeter/energyServer/smart Meter/1/measurements?c=5

The JSON-data, which is processed by the UI, can be obtained by extending the URL with .json. Thereby, the structure of the naming scheme we used to access the server and its components can be specified as follows:

http://[serverAddress]/emeter/energyServer/...

- *...[gatewayControl]*
- *...smartMeter/[resourceControl]*
- *...smartMeter/[UID]/[measurementControl]*

The *gatewayControl*, the *resourceControl*, and the *measurementControl* field respectively specify the action to be performed and can be substituted according to Table 1. UID refers to the unique identifier of the particular smart meter. Note that the table does not provide a complete overview of all available commands; its goal is more to provide a general idea of the actual functionality.

The third component is the UI. It uses the functionality provided by the gateway to access the data base and to dynamically present real-time information on the energy consumption. Besides the possibility to follow the consumption and control the gateway using any web browser, we developed a content-rich UI in Objective-C (ObjC) that runs on a mobile phone. In order to get the real-time results and measure single devices, the UI calls the gateway URI and converts the resulting JSON messages from the data base. Using the same principle, it is also possible to store user-generated content in the database. This enables users to store data, such as personal details about the household and the conducted measurements of devices, on the gateway.

The developed architecture shows a possibility how future electricity monitoring systems can be designed to provide real-time and fine granular feedback. To overcome the limitations of existing monitoring solutions, our architecture uses components that will be integrated in many households in the course of smart meter implementation. Through the RESTful API, the gateway integrates the readings of the smart meter into the web and makes them easily accessible for humans through a web browser or a mobile phone application. Furthermore, through the use of JSON, other applications can be easily developed on top of the system.

Table 1. Control command overview

Component	Keyword	Action
gatewayControl	status	shows the status of the gateway components
	restart	restarts the gateway
resourceControl	*	lists all smart meters
	new	creates a new resource
measurement Control	kWh?timespan	kWh per timespan
	measurements?c/*	*c* last/all measurements
	measurements? d/m/y/avg	measurements of the day/month/year/average

[3]JavaScript Object Notation, http://json.org

4. THE MOBILE USER INTERFACE

In order to overcome the drawbacks of existing energy monitoring systems, we wanted the UI not only to be attractive and easily-accessible, but also to provide information and functionality that motivates over a long period. Furthermore, for users it is desirable to know how much single appliances consume as well as to have the information at hand when needed. Thus, we decided to develop a portable UI that is based on a mobile phone application. It provides the following major functionalities: live visualization of the current electricity consumption, a historical view of the energy consumption, the possibility to interactively measure the consumption of any electrical appliance in the house, and an appliance summary view that gives an outline of the costs and the corresponding equivalents per measured device.

The overview screen of the UI (Fig. 3 left) is a scale that provides real-time feedback of the overall electricity consumption of the household. The scale is divided up into four colored parts that help users distinguish how energy-efficient their behavior is. Furthermore, the scale is self-learning in the sense that, after an initialization period, it automatically adapts colors and range according to the energy consumption of the household. In that way, the different colors classify the current energy consumption of the household and provide users feedback about how their current electricity usage compares to their historical consumption. The blue part indicates the base load of the household; the green segment sprawls up to the first quartile of the measurement values stored in the database; the yellow segment ranges from the first to the second quartile; and the red segment extends above the second quartile. This enables users to easily classify their energy consumption. For example they can discover whether there are still appliances running when leaving the house, just by comparing the current consumption to the blue part of the scale.

The history screen (Fig. 3 right) shows historical consumption data in form of a load curve. In addition, it presents the accumulated consumption for the previous days, weeks, or months. Each of the vertical bars is color-coded depending on how much energy was consumed in the corresponding period. Thus, it lets users compare the electricity usage over different time periods and allows for drawing conclusions on how a change in behavior relates to the overall consumption.

The measurement screen (Fig. 4 left) allows interactive detection of the consumption or standby usage of a single or multiple ap-

Figure 3. User interface accessing real-time metering data

pliances. To perform a measurement, the user simply has to activate the process by pressing the start button and thereafter turn the device that should be measured on or off. The corresponding result is shown in the display right away. After the measurement, the user can save the measured device to a list of appliances. The UI offers further possibilities for personalization (Fig. 4 right). For example, users can take pictures of the measured appliance, assign a location, and adjust its utilization to calculate the incurred yearly costs. In case a device category is selected, the UI displays category-specific guidance on how to save energy.

The devices screen (Fig. 4 middle) contains an overview of all the previously measured appliances. It provides the possibility to sort the measurements according to the assigned location or the used power, so the biggest energy guzzler appears at the top.

To evaluate the proposed system and to gather first insights on user reactions to the developed UI, we tested the system's functionality with 14 users. In order to become familiar with the application and uncover potential problems, participants had to complete a list of given tasks that guided them through the different application views. While conducting the tasks, we took notes about their reactions. Afterwards, participants were given further time to experiment with the system. They successfully completed most of the tasks, which included navigation through the different views as well as interactively measuring single devices. Most significantly, we discovered that many participants experimented with the measurement functionality. From that we can conclude that the interactive component of the system plays a decisive role.

5. CONCLUSIONS AND FUTURE WORK

In this work, we presented a system that allows users to interactively explore their energy consumption. It is based on a smart electricity meter and thus provides insights on the design and requirements for future home energy monitoring systems. By designing a portable UI on a mobile phone, we provide the electricity feedback that is ideally desired by the user to better understand the origin of the consumption. That is, in real-time, on device level, and at hand when needed. We also surpassed the limitations of other solutions that require complex installation or are battery-dependent, as our system uses components that are integrated in the users' everyday life.

The prototypical deployment of our system concentrated on the technical aspects and the UI, future work will include a detailed evaluation of the prototype and the developed UI. Aspects to be evaluated include trials and a user study to find out what functionality and visualization users understand and prefer on such a mobile UI. In addition, we will investigate how such a solution performs in terms of energy savings in comparison to other feedback solutions available today. Our system enables the real-time

Figure 4. User interface measuring the consumption of a device

monitoring of the entire electricity consumption as well as the measurement of the actual consumption of devices that can either be switched on/off or those that can be plugged in/out. However, there exist devices in the household that consume a recognizable amount of energy, such as the fridge and the freezer, which do not fall in this category. These devices cannot easily be measured by the habitant. Therefore, we will investigate the potential of pattern recognition algorithms applied to the measured load curve to automatically recognize devices. Another aspect to be addressed by future work is to evaluate the potential the system offers to influence the behavior of habitants in terms of energy usage.

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