Smart Residential Energy Systems – How Pervasive Computing can be used to conserve energy

Markus Weiss, Wilhelm Kleiminger
{mw, kleiminger}@ethz.ch
Institute for Pervasive Computing, Bits to Energy Lab, ETH Zurich
Universitätstr. 6, 8092 Zurich, Switzerland

1. Introduction

Energy consumption in buildings accounts for about 40% of total energy consumption [1]. The residential sector alone has seen a rise in electricity consumption by 54% since 1991 [2]. To a large extend, this increase can be traced back to the growing number of electrical appliances. While most large appliances (e.g., dishwashers, washing machines, etc.) have become more efficient over the years, the numerous small appliances introduced into residential environments contribute significantly to today's energy consumption. This growing number of devices and the lack in consumption transparency make it difficult to address the question of how to conserve electricity. Fortunately, "smart" pervasive computing technology can help to acquire underlying information and through combination with feedback and automation capabilities leverage energy saving effects thereafter.

Automated energy conservation is the most desirable form of saving energy. Due to the large variety of appliances, however, this is difficult to achieve in residential environments. Energy savings in such highly individualized spaces can only be achieved if we are able to plug into this diversity. The networked interconnection of physical appliances (Internet-of-Things) enables us to do so by re-using existing devices as sensors and actuators. Technological progress, such as smaller and more powerful hardware, embedded into everyday objects (e.g., low-power sensors, embedded Web servers, etc.), facilitates this change. Combined with features becoming available through the smart grid (e.g., demand response) automated energy savings can be realized in the background and mostly invisible for users.

When automation fails, pervasive computing helps to achieve savings by taking consumers "in the loop". User-induced saving effects mainly result from two factors: First, the energy demand of many appliances and systems is highly dependent on how we operate them. Without the required information, energy consumption in identical homes can easily differ by factor two or more, depending on the inhabitants' behavior [3]. Second, the decision to invest in efficient appliances and energy saving technologies is up to the user. Therefore, awareness and willingness to take action are crucial and can only be achieved with adequate information at hand.

Thus, we argue that conserving energy in residential environments requires the use of automated savings wherever possible as well as the provisioning of consumption information where necessary. In this paper, we show how using an infrastructure based on "smart" pervasive computing technology can help to achieve both: user-induced energy saving effects through information while at the same time opening new possibilities for automatic energy conservation.

2. A pervasive data acquisition infrastructure

In order to be effective, residential energy feedback and control systems have to feature a low usage barrier, present the feedback on a user interface that is integrated into daily life, and provide feedback in real time on the overall energy consumption as well as on the consumption of individual appliances [4]. This poses major challenges on the practical realization with respect to cost, usability, installation, and calibration [5]. Existing systems can be classified according to the number and type of sensor used to acquire the information (see Figure 1).

Single sensor solutions use one sensor to gather the information that is typically installed close to the household meter or in the fuse box. This makes it hard to self-deploy the system, but reasonable in price. Once installed these systems feature a low usage barrier, since the overall consumption is typically directly available. However, to achieve consumption information on device level, more sophisticated approaches that require intensive calibration and training are necessary. Moreover, these solutions typically act as feedback solutions only and cannot automatically conserve energy.

Multiple sensor systems mostly feature control capabilities and a high device-level accuracy since the electricity is measured directly at the individual device. However, this advantage comes at high cost, as in principle every appliance has to be equipped with a sensor. At the same time this is user-discouraging, since most users are not willing to install a high number of sensors or smart power outlets throughout the house. Unless all devices are equipped with a sensor by default, these systems thus typically only cover a subset of all electricity consuming devices.

In contrast to existing energy feedback solutions, we specifically designed a system that contains a low usage barrier (e.g., through using components that are ubiquitous in the

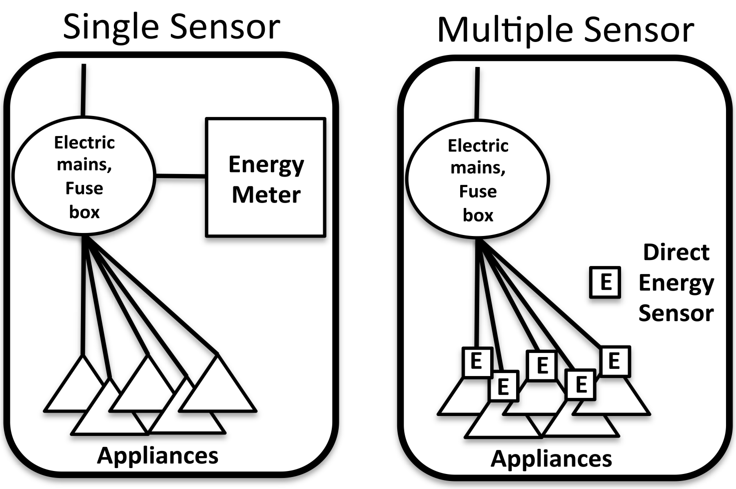

Figure 1. Single sensor and multiple sensor systems. The first measure the electricity usage with a single sensor, and from that try to infer what appliances are running in the households. The latter typically require an electricity sensor to be installed inline with every appliance.

home environment). It pays special respect to usability issues, which is crucial for the adoption and has been neglected by other energy feedback systems.

Our data acquisition infrastructure [6] consists of three interconnected components (Figure 2): A smart electricity meter, which is going to be (mandatorily) installed in large numbers in Europe and the US. It monitors the total load of the household and, compared to classical electricity meters, contains a communication interface for data retrieval. We additionally incorporated a gateway (Figure 3) that manages the recorded data and handles the requests from the user interface, which is realized as a mobile phone application. Since being based on a smart meter and a downloadable smart phone application, the proposed system is simple to install. By providing real-time feedback on a mobile phone, the system features both: feedback on a device that is already part of users' life, as well as the possibility to provide instantaneous feedback that is at hand when needed. The system samples the total electricity consumption at a frequency of 1 Hz for different physical quantities (i.e., real, reactive, distortion power, etc.) and processes the recorded metering data for automation and information purposes.

Data analytics methods are applied to provide detailed energy feedback at no extra cost. Further, we use disaggregation algorithms that disambiguate the recorded total load to device-level consumption and usage information as basis for automated recommendations for conserving energy. We also use this information together with data from other ubiquitous sensors (e.g., location) to derive occupancy state of the house. This serves as input for an algorithm that optimizes the thermostat control strategy and thus enables automated conservation of heating-related energy.

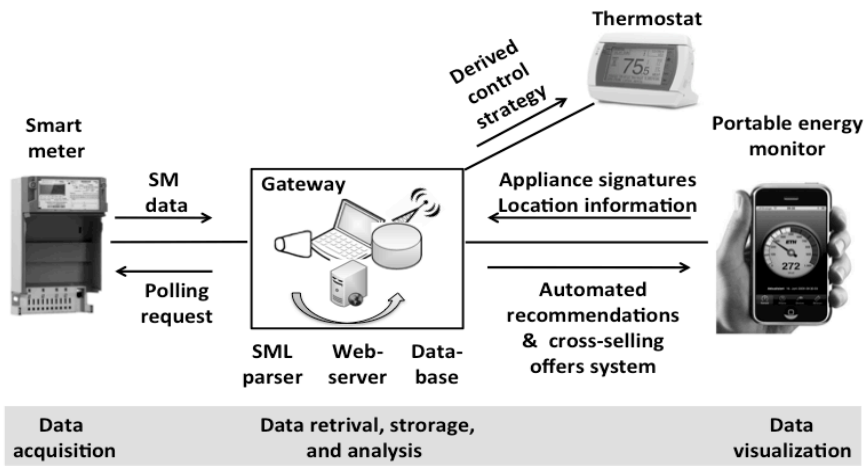

Figure 2. System infrastructure: A smart meter records the electricity usage and communicates with a gateway that runs a webserver, a database, and a parser. It takes care of data processing and request handling from the user interface, which is implemented as a smart phone application. The derived heating control strategy is used to automatically operate the thermostat.

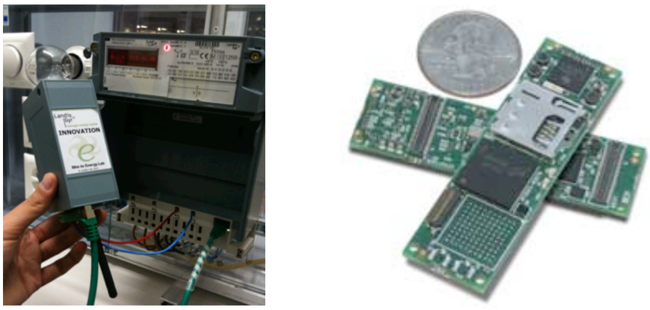

Figure 3. Smart meter clip-in module (left) and Gateway hardware (right). The gateway is implemented on an embedded device called Gumstix. It is based on a Texas Instruments chip with a CPU speed of 600MHz, 256MB DDR RAM, 256MB NAND flash memory, and a Wifi, and Ethernet module for communication purposes.

3. Contribution and Outlook

Our system has currently been deployed in four Swiss households for a year. The data gathered by the electricity sensor combined with ubiquitous sensors such as mobile phones are used as input for our post processing data analysis. Besides providing detailed household-specific energy feedback, we have developed algorithms that allow determining the electricity consumption of any switchable appliance with the help of the mobile phone as well as disaggregating the total energy consumption to the consumption of individual devices. This allows users to identify the consumption of an individual appliance in a simple, explorative way. In the background – invisible to the user – appliance signatures are logged to provide a baseline for automatic load disaggregation [7].

Based on the recognition results, automated recommendations are pushed to the user interface that should drive user-induced saving effects. This not only increases users' energy literacy, but also leverages the added value of smart metering. Appliance level consumption information can be used to create new business models (e.g., through providing replacement offers for detected non-energy-efficient devices).

We tested our system in a laboratory study that simulated a real environment with ten different devices over an extended time span. With a recognition rate of about 90%, the results of the evaluation confirm the suitability of the general approach and encourage us to intensify research and conduct refinements based on the data gathered from the real world deployment. This also includes accuracy improvements through the extension from one to three phases and a module for auto-identification of non-switchable heating and cooling devices. In the future, we envision aggregating appliance signatures from different households in an appliance signature database that helps to improve the recognition rate.

Our recent research focuses on leveraging the gathered metering data to realize automated heating-related energy savings through novel control strategies based on the existing infrastructure [8]. This is particularly relevant since the energy spent on heating can reach up to 70% of the total residential energy consumption - as shown in the case of Switzerland [9]. The information from the smart meter can be enhanced opportunistically with data from mobile phones and more traditional occupancy sensors (e.g. PIR sensors, reed switches) to infer household occupancy state (Figure 2). Based on this information, we optimize the heating control strategy to automatically adapt home temperature and thus account for automated energy savings. By evaluating the accuracy of the individual and combined sensor information we can make an informed choice about how to control the thermostat.

However, a simple reactive strategy is not sufficient to control heating. It takes a considerable time for a building to reach a comfortable temperature. The ramp-up times need to be reduced by using a stochastic model to predict future occupancy states. We are planning to use a Markov Chain to model room level occupancy. The opportunistic approach in conjunction with the device recognition helps us to obtain this information.

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