ICT for Green – How Computers Can Help Us to Conserve Energy

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ABSTRACT
Information and communication technology (ICT) consumes energy, but it is also an important means to conserve energy. Classically, it did so by optimizing the performance of energy-using systems and processes in industry and commerce. In the near future, ICT will also play a critical role in supporting the necessary paradigm shifts within the energy sector towards a more sustainable generation of electricity. However, with the advent of “smart” technology from the ubiquitous computing domain, further possibilities to reduce the growing energy consumption in the residential sector are now emerging. In that respect we discuss how taking the consumer “in the loop” can realize energy savings on top of efficiency gains through automated systems, and we describe a prototype application that aims at inducing a desired behavioral change by providing direct feedback on household electricity consumption.

Categories and Subject Descriptors
J.m Computer Applications – Miscellaneous, J.7 Computers in Other Systems, H.5.2 User Interfaces.

General Terms
Measurement, Human Factors, Economics.

Keywords
Smart meter, advanced metering, smart grid, energy conservation, feedback systems, behavioral change.

1. INTRODUCTION: ICT AND ENERGY
Information and communication technology (ICT) is one of the pillars of today’s society – it not only has a major impact on our professional and private life, but it also becomes one of the most important drivers of economic growth. In the past, however, economic development with its steady increase in productivity, consumption, and mobility usually went hand in hand with increasing usage of natural resources. Even though for most countries energy consumption grew slower than the gross domestic product, the world-wide yearly energy consumption steadily increases and reached 139,700 TWh in 2007, with approximately 12% (16,429 TWh) final electricity use [19].

While ICT with its favorable effect on the economy is certainly an important indirect cause for the overall use of natural resources and energy, the total energy consumption of ICT itself is difficult to estimate. Studies vary with respect to the definition of ICT, the methodology to generate the estimates, and the share of energy consumption of a device that is attributed to ICT. In a recent study published by the European Commission, total electricity use of the ICT sector (without consumer electronics) in the European Union (EU-27) is estimated to 119 TWh in 2005, which corresponds to 4.3% of the overall electricity consumption, or 0.6% of total energy consumption [8]. For the U.S., Laitner et al. [22] estimate that ICT’s share on electricity consumption was around 8% in 2008.

This share by the ICT sector on total electricity consumption is certainly noteworthy. It deserves attention and calls for adequate measures, in particular because it is increasing fast – for the EU-27 by about 50% within 15 years in a “business-as-usual” scenario [8]. Indeed, quite some effort has already been undertaken to address this issue, striving for low-energy ICT systems. The drivers are manifold and include several incitements beyond environmental considerations (“green ICT”), such as the cost of operation for large data centers, challenges related to heat dissipation of processors, and the operating lifetime of battery-supplied devices.

However, high hopes also rest upon ICT to reduce resource and energy consumption in other economic sectors, and thus to mitigate global warming. This could mean, for example, to improve with the help of ICT the energy efficiency in established processes (i.e., increase the ratio of a relevant target variable such as productivity or comfort to energy consumption), or to enable by ICT new concepts to generate, allocate, distribute, share, and use energy in a resource-efficient and environmentally-friendly way.

As, alongside rising energy cost, environmental sustainability became more important in recent years, a growing number of large infrastructure systems and processes were optimized for lower power consumption. Here, ICT with its general potential for large-scale simulation, optimization, and real-time control plays an outstanding role. In the business context, ICT also helps to come to better decisions with respect to resource and energy consumption – examples include optimization of production and supply chain processes [18] or environmental information systems [14]. Investments in energy saving technologies often also pay off financially, in particular in times of rising energy cost.

The energy productivity indicator (primary energy supply divided by the gross domestic product) in the OECD and BRIC countries
fell from 0.32 in 1971 to 0.21 in 2005 [34]. This trend can be interpreted as a decoupling of energy demand and economic growth. With empirical data correlating use of ICT positively to economic growth [42], there is strong evidence that ICT is an important driver for better energy productivity. Laitner et al. estimate that in recent years for every one kilowatt of energy used by ICT equipment, approximately 10 kilowatts were saved economy wide through productivity gains and efficiency improvements [22].

Thus, ICT is an enabling tool for energy efficiency (typically as a side effect of process or infrastructure optimizations) with a tradition of many years already. The recent slogan “ICT for green” suggests, however, in addition to this a more direct use of ICT to energy conservation. Examples include reducing commuting by teleworking or the support of energy savings in home environments. Since already about one third of the electricity is consumed by households, the latter represents an important sector.

However, while industrial processes and public infrastructures still offer many opportunities for energy saving through automation and optimization with classical ICT, this is more difficult in a home environment. Classical measures to reduce the energy consumption of households are limited, essentially they consist in the use of more energy-efficient appliances, including the reduction of stand-by losses. Fortunately, however, technologies from the ubiquitous computing domain (such as low-power sensors, cheap wireless communication, embedded Web servers, etc.) now become available which offer new opportunities to save energy, even without direct user involvement. Example scenarios include automatically detecting activity in the home [44], so that the heating or the air conditioning can be adjusted accordingly, or the fridge that communicates in an “Internet of Things” [27] with a smart household electricity meter in order to use, when available, cheap excess energy in the power grid (for example produced by intermittent renewable energy sources) to cool below its normal temperature (and thus store energy).

Although “ICT for green” alone will not save the planet, we believe that “smart” ICT can, when it is being used consistently, reduce domestic electricity consumption by at least a few percent. In the rest of this paper we shall provide some arguments that support our belief. And in any case, electrical energy that doesn’t have to be produced because it isn’t needed, is certainly the “greenest” energy.

**Positioning and structure of this paper.** With respect to energy conservation and ICT, one is usually concerned with the issue of “less energy for ever more computers”. Instead, however, we concentrate in this paper on the dual issue "more computers for less energy". The importance of the latter is motivated by a set of far-reaching paradigm shifts in the energy sector, which we will describe in the subsequent section. Thereafter, we will discuss the potential of ICT to favorably change consumer demand for energy. We outline how integrating the consumer in ICT-driven energy conservation efforts can both foster the adoption of green products and realize efficiency gains on top of savings from automated systems. We then discuss how “smart” ICT can help consumers to get immediate feedback on household electricity consumption, and we exemplarily describe a prototype application (the eMeter) that aims at inducing a desired behavioral change by providing that feedback. We conclude the paper with an itemization of important fields of future work.

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1 EU-27: 29% in 2005 [8]; U.S.: 37% in 2008 (www.eia.doe.gov/aer/).
2 With a share of 39.3% in 2007, electricity generation is the leading source of carbon dioxide emissions in the U.S. [45].

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2. **PARADIGM SHIFTS IN THE ENERGY SECTOR AND THE IMPORTANCE OF ICT**

The new role of ICT as a more direct enabler of a sustainable development gives rise to a number of important challenges. These include questions such as how the technology can contribute to the optimal use of renewable energy, how to control a changing network topology with a huge number of energy providers, how to help to establish new energy services and solutions, or how ICT can best contribute to smart energy market places. The interest in new ICT solutions is mainly driven by a number of (partially interwoven) paradigm shifts within the energy sector, which we now briefly discuss.

**From “unlimited” supply to a precious resource.** Building new atomic or coal-based power plants has become unpopular in most industrialized countries. Furthermore, the debate about the effect of carbon dioxide on global warming and the political pressure to decrease carbon dioxide emissions not only favors “green” energy, but also incites to reduce energy consumption in general. Conserving energy is now even becoming “chic” in some circles, and means to reduce energy consumption without decreasing the standard of living are thus welcome.

**From regulation to deregulation.** Politics, in particular in Europe, introduced a number of measures in recent years to open the traditional oligopolistic and regulated market of energy production and distribution. As new players (independent main operators, resellers, billing service providers, etc.) enter the market, the interactions across company borders are intensified. The rise of complex and timely interactions necessitates new ICT solutions, for example to avoid costly media breaks in processes such as billing and to efficiently exchange control information that is necessary to operate the electrical power grid. Deregulation also leads to a stronger competition among the players, which, together with a growing demand for green products and services (accentuated by some political pressure) forces companies to clearly position themselves on the market. This even leads to promoting “smart energy conservation products and services”.

**From centralized to distributed generation.** Local renewable energy generation, for example by solar panels on the roofs of buildings, is becoming more and more important across energy that is not needed locally should be fed into the grid. One can also imagine that in the future the batteries of a parked electric car serve as a buffer for energy that send power back to the electrical grid when demand is high. Managing a bidirectional grid and making optimal use of various small (and intermittent) energy sources (while guaranteeing high reliability) is a non-trivial issue that requires an adequate information and communication infrastructure.

**From control to cooperation.** Traditionally, electricity generation by power plants had to meet momentary consumption. In the future, power consuming devices will more and more make the best out of the energy that is currently available. More precisely, one expects that in a “smart grid” energy consuming appliances, energy generation units, power distribution units, and various other intermediaries negotiate and cooperate to optimize their situation. For that, suitable ICT-based market platforms are required, which would then also enable new forms of energy brokers or even virtual power plants [38] formed by distributed small generators such as combined heat and power (CHP) plants.

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3 Such as the energy efficiency software company OPower (www.opower.com) which helps utilities meet efficiency goals.
From energy consumption to smart energy usage. Many renewable energy sources are inferior to conventional power stations with respect to the ability to plan and control the energy generation. Especially generation by wind turbines or photovoltaic systems can lead to high fluctuations of energy supply in the power grid. Such fluctuations (and other allocation irregularities) sometimes even lead to negative energy prices. This phenomenon can at least be mitigated by smart devices that consume or store energy when excess power is available, leading to a better balancing of supply and demand (i.e., “demand follows load” instead of “load follows demand”). This not only requires an ICT infrastructure for the cooperation of smart appliances, but also measures such as smart meters, dynamic prices, and near real-time forecasting and planning models that take various context conditions (weather, time, consumption habits, etc.) into account.

The implementation of these paradigm shifts is a major undertaking that will not only take quite some time and induce high investments, but that also has to be supported by a massive use of "smart" ICT. Fortunately, recent advances from domains such as networking, embedded systems, building automation, and ubiquitous computing complement classical ICT in that respect.

While even in households (which are typically complex and individualized environments) "smart" ICT can often act in the background and conserve energy by optimizing and automating some processes, further energy savings in such environments require – at least to some extent – the involvement of the consumer. This is a challenge, since human interaction is typically regarded as a loss of comfort, and saving energy is often not seen as a key objective but as a necessary constraint. Nevertheless, providing feedback to consumers about the energy consumption of their various activities and appliances should motivate some to change their habits and thus to contribute to the conservation of energy. We will discuss this issue and appropriate concepts and technologies in more detail in the following sections.

3. ICT TO INDUCE BEHAVIORAL CHANGE

While automation and energy-optimized systems will be without doubt essential to reach the saving targets, the adoption of these systems and the user behavior in general has a major influence on the energy demand. ICT can play an important role in that respect because it can assist individuals to make better informed decisions or reward socially desirable behavior in their daily life. In fact, taking the user in the loop can not only help to guide individuals when using energy consuming devices, but also induce favorable decisions, e.g., when purchasing electrical devices, heating systems, and family cars with lower energy demand.

There exist many situations where people – despite their general intention to protect the environment – do not take even the simplest measures to reduce their energy demand. As an example, virtually all PCs and imaging equipment feature automated power saving techniques which set screens or CPUs in low-power mode after a period of user inactivity. These features, however, are all too often not active in both private and office environments, even if they are pre-installed on most devices. As another example, consumption in identical homes, even those designed to be low-energy dwellings, can easily differ by a factor of two or more depending on the behavior of the inhabitants [6].

The existence of many unnecessary energy sinks can be mainly attributed to a lack of transparency in energy consumption [3]. An amazing example of a non-anticipated growth in energy demand is brought by the market success of coffee machines (in particular small espresso machines) in Swiss households and offices. For convenience, these machines often keep the water or beverage hot or even preheat the cups. In Switzerland alone, these devices consume approximately 400 GWh per year in standby mode [32]. Compared to approximately 1000 GWh per year in total for food preparation with kitchen stoves, baking ovens, microwaves, and similar cooking machines (including coffee makers!) in the same country [33], the additional demand is enormous and was virtually unnoticed or at least not ascribed to the device by most owners.

Reasons for lost saving potentials originate at least in part from a lack of knowledge on the personal energy consumption, the difficulties to investigate the efficiency of the own equipment pool, and the rather limited motivation to adjust the personal behavior. In order to mitigate these deficiencies, the European Union initiated in 2006 an Action Plan for Energy Efficiency which aims at “realizing the potential which underscores the need for a paradigm shift to change the behavioral patterns of our societies so that we use less energy while maintaining our quality of life” [5].

In this context, high hopes are placed on smart metering infrastructures which provide real-time information flows and enhanced ways to manage and control energy consumption of households. However, a meta study over 64 pilot projects we have conducted to better understand the efficiency gains induced by smart metering and monthly billing showed a rather disillusioning picture concerning the achieved saving potential. After sorting out studies with methodological weaknesses and low explanatory power, the meta study showed energy savings between 1 and 2 percent only. With direct feedback (e.g., using in-home displays), additional savings in the order of 1 to 2 percent have been realized (see Table 1 below for a selection of methodologically sound pilot studies with above average efficiency gains).

The typical efficiency gains clearly lag behind common expectations. It is also noteworthy that many participants of the pilot projects were reluctant to have the metering technology installed. A quick decay of involvement shortly after the devices have been introduced was also common, and sustainable behavioral changes have only been realized within a small subgroup. One could hence conclude that while many people claim that saving energy is important, the willingness to act accordingly is rather limited [39]. The situation is not that hopeless, however. A closer look at those particular pilot studies which used advanced motivational cues (beyond promising future cost savings) typically succeeded in engaging a large number of users over the duration of the campaign, achieving significantly higher energy savings.

Based on these observations, we compiled a set of proven measures to induce behavioral change. The measures can be categorized into two groups, one supporting the rational behavior (informational support), and the other leveraging partly irrational motivators (intrinsic motivation and social positioning). Both categories are outlined below.

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4 For example, at the European Energy Exchange (EEX), hour contracts noted -500.02 Euro/MWh at Oct. 4, 2009 in hour 2-3.


6 E.g., observations that only lasted less than two months, contained no control group, were accompanied by other efficiency measures (such as intense personal energy consulting campaigns), or which included only a priori interested participants.
ambition can be positively influenced by offering appropriate goals, resulting in higher persistence. Important influencing variables are attainability, self-efficacy, and the source that defined the goal. Goals that one sets oneself, for example, are more likely to be achieved than those set by external sources [24]. The degree of ambition can be positively influenced by offering appropriate defaults or by stating that attachment figures or authorities made a specific selection. Energy monitors, for example, can combine defaults, goal setting, and feedback on the state of the current performance, while providing advice to better reach the objectives.

Energy budgets appear to perform well to increase intrinsic motivation. In a British pilot project, pre-paid electricity tariffs with simple interfaces to keep track of the current balance positively influences saving efforts [7].

Comparisons with other entities have already been outlined as informational cues. They are especially effective when the peer is chosen to be similar to the recipient of the information, lives in close proximity (e.g., the same village), has the same profession, or is member of a familiar or admired group [28]. Moreover, people tend to act in a socially preferably way when their behavior becomes visible to others. First projects use social networks such as twitter or facebook as a platform for energy efficiency activities, but they have not yet gained much attention.1

“Smart” ICT renders possible the combination of informational support and means to foster intrinsic motivation. In an ideal scenario, the deployment of energy measurement devices and energy saving services is embedded in a wider campaign, game, or competition to get users involved. Lotteries have shown to be efficient as a first motivator,2 but other incentives which can be easily facilitated by ICT have not yet been tested on a larger scale.

We will describe a prototype system and demonstrator (the eMeter) to test and evaluate some of the abovementioned concepts below, after surveying and briefly discussing in the next section the most important energy feedback systems that have been developed in recent years.

### 4. Feedback on Electricity Usage

There already exist several energy monitoring solutions that provide feedback about the electricity consumption. They aim at helping users to understand where energy wastage occurs and thus try to establish a basis for conscious energy usage. These electricity feedback solutions can broadly be classified into two categories according to the number (and type) of sensors used to acquire the electricity consumption information.

#### 4.1 Single Sensor Approach

The first category consists of single sensor solutions, which in the first place are limited to display the aggregated consumption of a circuit or even the entire power demand of a household. Several products such as Wattson10, Onzo11, Current Cost12, Power Cost Monitor13, and TED-100014 are available. Once installed, they visualize the entire attached electricity consumption on a display unit. However, installation on circuit or household level is complex and users are thus often discouraged to deploy such products. Furthermore, these solutions suffer from the fact that mainly for safety reasons the wiring around the household meter is not at all accessible in many countries and modifications require a technician. Another drawback is the unsuitability to provide users with

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1 Informational support. It is widely accepted that communicating consumption data by a mere value and physical unit is not adequate for most people [26]. For a more thorough interpretation, analogies are regarded as helpful, which can also increase the time a user reflects and processes the information. The type of analogy must be carefully chosen, however, to guide the user in the desired direction, e.g. specifying the size of a solar panel that is required to produce an energy equivalent, for example, manifests the feeling that the amount of energy is high; mentioning the number of tea cups that can be heated up has the opposite effect.

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Another important way to support the placement of the personal consumption in a wider context is a comparison with other entities (families, homes, etc.). Care must be taken when choosing average values: showing individuals that they perform better than the average regularly leads to reducing the effort paid and ultimately to higher energy demand. The same effect occurs when recipients are confronted with average values that are by far better than their own performance values, as this often leads to defining the all-too-difficult to achieve goal as not worth pursuing [41].

When done adequately, the informational support increases the willingness to act. In order to transform the momentum into change, the consumption data should be accompanied by concrete and context-specific advice, an offer of further assistance, or at least some request for self-commitment.

Intrinsic motivation and social positioning. While many people agree upon the importance of their personal engagement, they often lack the motivation to ultimately take action. Established concepts from consumer research and marketing appear to be promising to increase the users’ intrinsic motivation also for goals such as conserving energy. The concepts include goal setting, the use of virtual budgets, and social comparisons.

Goal setting theory, in brief, asserts that goals lead to more effort and higher persistence. Important influencing variables are attainability and self-efficacy, and the source that defined the goal. Goals that one sets oneself, for example, are more likely to be achieved than those set by external sources [24]. The degree of ambition can be positively influenced by offering appropriate analogies are regarded as helpful, which can also increase the time a user reflects and processes the information. The type of analogy must be carefully chosen, however, to guide the user in the desired direction, e.g. specifying the size of a solar panel that is required to produce an energy equivalent, for example, manifests the feeling that the amount of energy is high; mentioning the number of tea cups that can be heated up has the opposite effect.

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feedback on the electricity consumption of single devices, which from a feedback perspective would be necessary to draw conclusions on how consumption and behavior relate to each other.

Some experimental systems try to disaggregate the entire consumption measured by a single sensor to provide more specific information about the electricity consumption on device level [28]. The aim of these non-intrusive load monitoring systems is to keep equipment cost and installation time at a minimum, but still obtain detailed energy use data. To determine what appliances are currently running, some of these systems simply measure the global power difference from one instant of time to the next; a principle that has been investigated by several researchers in the past [1], [9], [37]. Other, more sophisticated approaches use statistical signature analysis and pattern detection algorithms to infer the devices from the current and voltage wave forms [23]. To achieve the disaggregation, these systems require either a priori knowledge about the household devices and their electrical characteristics, or they induce a complex calibration and training phase involving the user, in which the system learns about the specific device characteristics. However, a priori knowledge is difficult to obtain in a world of fast changing small appliances, and manual training induces a high usage barrier. Furthermore, appliances whose power consumption vary or overlap with other devices are a particular challenge to disaggregation algorithms.

A more sophisticated idea has been explored by Patel et al. [35]. The authors developed a system that relies on a single sensor that can be plugged-in anywhere to the electric circuit of a household. It listens on the residential power line to detect unique noise changes that occur through the abrupt switching of devices. With some probability, this approach allows to determine the status (such as on, off, stand-by, etc.) of an appliance. To infer the actual electricity consumption of a device, this information then has to be combined with the measurements of a smart meter.

4.2 Multiple Sensor Approach

Multiple sensor approaches can be divided up into direct and indirect systems. Direct systems require in-line sensor installation with every device or circuit. Indirect sensing systems use a central electricity meter together with additional context sensors to monitor the energy consumption.

Direct sensing systems mostly come in the form of smart power outlets. They are relatively easy to deploy and several products exist. Once installed, they measure the attached load and display the measurement data on the unit itself or transmit the data wirelessly to a remote display. However, these systems lack the possibility to aggregate the consumption of multiple sensors and to fuse the different data into a comprehensive picture.

To surpass this limitation, other work has focused on developing systems that combine multiple power sensors. Guinard et al. [13] realized a system that enables the integration of smart power sockets (“Ploggs”) that communicate their measurements via Bluetooth or Zigbee. A gateway is responsible for the discovery of the smart sockets in range. It also makes their functionalities available as resources in the Web and offers local aggregates of device-level services (e.g., the accumulated consumption of all sockets). Jiang et al. [20] developed a system where sensors measure the power consumption at the outlets and communicate the values over a wireless IPv6 network to a server that populates a central database.

Multiple direct sensing systems all suffer from the fact that deploying a large number of electricity sensors (i.e., meters) throughout the house quickly leads to high cost. Indirect sensing systems try to remedy this by keeping the intrusion of the electrical system at a minimum. Instead of many power meters they use other types of context sensors. In [21] Kim et al. describe a system that uses a single electrical sensor to measure the entire electricity consumption of the household together with additional context sensors (such as light, acoustic, and electromagnetic) that help to infer which appliance is currently operating from the measurable signals it emits. Within a defined set of appliances the authors show that the system can estimate device level power consumption within a 10% error range. The system’s performance, however, highly depends on the right calibration of the distributed context sensors as well as on their correct placement, which is not an easy task for the average user.

4.3 Feedback: Characterization and Outlook

Table 2 summarizes the main advantages and disadvantages of the different electricity feedback systems. Single sensors systems are hard to deploy, but reasonable in price, and once installed they feature a low usage barrier. Since the single sensor is typically installed close to the household meter or in the fuse box, the overall electricity consumption is easy to monitor. However, to achieve information on device level, more sophisticated approaches that require calibration of the algorithms are necessary. In addition, due to the vast variety of electrical devices, the accuracy of these systems is to a certain extent limited.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Single sensors</th>
<th>Multiple sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>Hard</td>
<td>Direct in-line</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Indirect</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Usage barrier</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Calibration</td>
<td>Hard</td>
<td>Easy</td>
</tr>
<tr>
<td>Device level accuracy</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Household level accuracy</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

In contrast, direct in-line electricity monitoring systems feature a high device level accuracy since the electricity is measured at the 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 increases the usage barrier, since most users are not willing to install a high number of sensors or smart power outlets throughout the house. Therefore such systems will typically only cover a subset of all electricity consuming devices of a household.

Lastly, indirect systems are in principle able to provide both, feedback of the entire electricity consumption and to a certain extent feedback on device level electricity usage. However, they require users to deploy different context sensors at the right place and necessitate complex calibration, which leads to both high cost and a high usage barrier.

The future pathway for electricity monitoring systems comprises the potential for a scenario in which household appliances, which

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15 For example “Kill a Watt”, www.p3international.com/products/special/P4400/P4400-CE.htm
16 Plogg, www.plogginternational.com
Today have only limited capabilities, become more powerful and smart. Through the integration of cheap and small embedded ICT components, they would sense and transmit their current energy usage together with other status information. Within the house, appliances could communicate with each other (and with the smart meter) via one of the established protocols (e.g., powerline, Zigbee, WLAN), but dedicated new technologies, such as digital-STROM\textsuperscript{17}, rivaling traditional domestic network technologies (BACnet, EIB, KNX, etc.), might also come up.

Moreover, the integration of embedded Web servers (based on REST and IPv6 / 6LowPAN) into household appliances should in future come at low cost. This would lead to a wide variety of application scenarios, for which the smart electricity meter (or a similar device) in a household could serve as a central component for data aggregation and analysis. At the same time, the embedding of a Web interface into appliances enables their full integration into the Internet [13]. Beyond the allocation of a device-specific Web page for status information, this allows to control the device and to process its data with the full power of Web 2.0 tools, giving rise to a “Web of Things” [12]. It is obvious, however, that with such possibilities one has to seriously pay attention to privacy and security issues.

5. THE eMETER SYSTEM

In this section, we present the eMeter system that is based on a single sensor approach and tries to overcome most of the limitations described above. By connecting a smart electricity meter with a mobile phone application, the system is particularly easy to use and realizes those features that seem to be most promising in terms of energy feedback. According to the literature [11], effective energy feedback has to

\begin{itemize}
\item feature a low usage barrier,
\item be presented on a device that is already integrated in users’ daily life,
\item be given frequently, in real time, and at hand when needed, and
\item provide the possibility to apportion the entire electricity consumption.
\end{itemize}

The eMeter system considers these issues. It achieves a low usage barrier by using a smart electricity meter, which is going to be mandatorily installed in households throughout Europe anyhow. This limits users’ necessary effort to the installation of a mobile phone application that can easily be downloaded from the Internet. Thus, the system is simple to setup and requires no modification by the user – neither around the electrical wiring, nor by deploying additional hardware at device level [46].

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. This is especially important since trials have shown that when using an additive battery-dependent display for electricity feedback, in 50\% of all cases users do not replace the battery once it is depleted [40]. This indicates a loss of interest after the users’ initial curiosity has been satisfied. Thus, since not being integrated into users’ daily life, this additive displays seem not capable to motivate users for longer time periods.

Lastly, useful feedback has to link specific actions to their effects by providing the possibility to disaggregate the overall electricity consumption. In order to take effective measures, it is key to understand how much single devices consume in standby or while operating [36]. Through an interactive measurement functionality, the eMeter system allows users to measure the electricity consumption of almost every device that can be manually switched on or off (see Section 5.2 below).

5.1 The eMeter Architecture

The eMeter system consists of three independent components (Figure 1): A smart electricity meter that monitors the total load of the household, a gateway that manages and provides access to the logged measurement data, and a portable user interface on a mobile phone that provides real-time feedback on the energy consumption and allows for users to interactively monitor, measure, and compare their energy consumption.

The system architecture is based on the REST (Representational State Transfer) paradigm [10]. REST is a resource-oriented approach that enables easy and seamless integration of physical resources to the Web. For that, REST proposes two basic principles: First, transferring the classical operation-centric model view into a data-centric view which essentially means that services now become resources that can be identified and manipulated (i.e., transferred, indexed, put on Web pages etc.) by using URLs. Second, the only available operations to access, update, delete, and create resources are the four main operations provided by HTTP (GET, POST, DELETE, PUT).

The first component of the architecture is the smart electricity meter (provided by Landis+Gyr in our implementation). It logs the load induced by all the devices attached to the residential power line. Compared to traditional electricity meters, a smart meter has a communication interface for remote meter readings (typically used by the energy utility company). In order to achieve real-time feedback, we exploit this functionality by requesting the meter to send out all available data via its interface every second.

The second component, the lightweight gateway, is implemented in Java and consists of a parser, a database, and a small Web server (based on the RECESS\textsuperscript{18}-framework). In order to continuously acquire the logged data from the smart meter in near real time, the integrated SML\textsuperscript{19} parser automatically polls the meter every second and stores the data it receives in a SQL database. Access to the gateway’s functionality, but also to the smart meter data, is provided by the Web server using URLs.

The smart meter measures a number of different physical values (e.g., actual load, voltage, current, etc.). Through the gateway, they all become hierarchically structured resources in the sense of REST. That is, each of the resources is implementing the four basic HTTP verbs. This is a powerful concept since it allows

\begin{itemize}
\item [17] www.digitalstrom.org
\item [18] www.recessframework.org
\end{itemize}

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\textsuperscript{17} www.digitalstrom.org

\textsuperscript{18} www.recessframework.org

\textsuperscript{19} Smart Message Language, www.t-l-z.org/docs/SML_080711_102_eng.pdf
accessing the meter data through any Web browser. For example, just by calling http://serverAddress/emeter/energyServer/smartMeter/1/measurements.json?c=last the resource measurement can be monitored. The corresponding GET-request issued by the Web browser is answered by the gateway, which first routes the request to the resource (that takes care of reading the “last” value) and then wraps the result in form of a HTTP or JSON message as shown below.

```json
{
  "smartMeter":
    "id": "1", "name": "Landis+Gyr", "createdOn": 1248102873,
  "measurements":
    "id": "9513463", "date": 1261401851, "watts": 322.483
}
```

While the gateway can support multiple formats, we decided to use JSON (as a lightweight alternative to XML) for interaction with other applications, and HTML for providing a human readable representation in a Web browser.

The **third component**, the content-rich user interface on a mobile phone, is realized in Objective-C. It exploits the functionality provided by the gateway to access the meter values and to dynamically visualize the information in real-time. For that it calls suitable URLs of the gateway together with the corresponding HTTP verb and processes the JSON message it receives in response. The user interface is also responsible to transmit user-generated data, such as details about the household and the appliances, to the gateway.

The architecture we described here is not restricted to the eMeter system. It shows in general how systems for home automation and similar tasks can be designed to provide real-time and fine-granular feedback. It also shows that the direct integration of smart physical objects into the Web infrastructure much eases the development of applications (such as the mobile user interface in our case). This is prototypical for an emerging concept known as the “Web of Things” [12].

### 5.2 The eMeter User Interface

In order to provide the important feedback features mentioned earlier, the eMeter user interface consists of the following four views (Figure 3): Live visualization of the current electricity consumption (a), a historical view of the energy consumption (b, c), a device inventory view that gives the energy usage and costs per measured device (d), and the measurement view (e) which offers the possibility to interactively measure the consumption of almost any switchable electrical appliance in the house.

**Figure 2. User measuring the power consumption of devices**

The **current consumption view** (Figure 3a) shows the current consumption in real-time. Moreover, the color coded self-learning scale allows users to assess how their current consumption compares to their historical consumption values (green to red). The blue part of the scale depicts the level of the household standby electricity consumption.

The **history view** (Figure 3b, 3c) shows a line chart of the historical consumption. Users can choose between different time periods, e.g. last hour, last day, etc. Together with the chart, the view depicts equivalents such as kWh and cost for the accumulated consumption over the last five selected periods (Figure 3b, lower part). The color-coded bars allow users to compare their historic consumption to a typical average household of their size and location. Moreover, the historic consumption view also provides budget calculations and projections (Figure 3c).

The **device inventory view** (Figure 3d) lists all previously measured devices. In addition, it allows users to step into the device details and assign a location (e.g., a room) as well as a particular utilization scheme (upon which the device’s cost calculations are based) to the device. It further provides the possibility to sort the measurements according to the assigned location or the used power, so that the biggest energy guzzler appears at the top.

The **measurement view** (Figure 3e) allows for interactive measurement of the electricity usage of most switchable appliances in the household. To perform a measurement, the user simply activates the process by pressing the green start button and thereafter turns the device that should be measured on or off. The corresponding result is shown on the display within seconds (Figure 2). The necessary calculations for this are performed on the mobile phone: At the moment the user initiates the measurement, the current consumption value determined by the smart meter is stored, and the measurement algorithm on the phone then waits for a signifi-
cant change of this value. After that it calculates the difference between the two values. (If incidentally another device starts or stops operating during the measurement interval, the result may be wrong. However, because this generates a spurious measurement, users are typically aware of this situation and may simply repeat the process.)

After the measurement, users can save the measured device to the list of appliances. The user interface offers further possibilities for personalization. For example, users can take pictures of the measured appliance, or detail its utilization to calculate the incurred yearly costs. In case a device category is selected, the user interface displays category-specific energy efficiency information and guidance on how to save energy.

5.3 eMeter: Summary and Future Work
The eMeter system allows users to interactively monitor, measure, and compare their energy consumption on household and on device level. The system tries to overcome the discouraging installation overhead of other typical energy feedback systems by making use of a smart electricity meter, whose installation is becoming mandatory in Europe and which provides high measurement accuracy on the household level. Assuming that in the future the lightweight gateway component will be integrated into the smart meter itself (or into another suitable device such as a DSL router or an Internet gateway), users would only have to download and install the mobile phone application which can easily be done within minutes or even seconds. Since the system does not require additional hardware, it comes at low cost and should in general have a low usage barrier.

The system’s device level accuracy, however, suffers from the single sensor approach. We try to surpass this by integrating a measurement functionality into the user interface that aims at providing users with an initial idea how much different devices consume. Provided that the small measurement interval is representative, it enables users to measure the electricity consumption of any switchable or pluggable device. Only the correct measurement of devices with variable or dynamic energy consumption (such as a laptop computer for example) could represent a bit of a challenge. However, there also exist some devices in the household that consume a non-negligible amount of energy, such as the washing machine or the freezer, which usually cannot just be turned on or off. For such devices that cannot easily be measured by the user, one of the automatic device identification methods described in Section 4 could be envisaged.

6. DISCUSSION
ICT can make a significant contribution to saving energy, both by autonomous optimization efforts and by inducing changes of user behavior. Yet, achieving the latter is not that easy: Having the somewhat disappointing outcome from first feedback systems with smart metering infrastructures in mind, one could indeed question the power of the “user in the loop” paradigm. However, the partly unsatisfactory results mostly seem to be a consequence of insufficient ways to motivate and engage the consumer, as notable efficiency gains have been demonstrated in many of the better organized settings (see Table 1).

Even if with feedback systems the direct savings are only in the order of a few percent, energy that is not produced because it is not needed is still the cheapest and most environmentally-friendly. Moreover, society should benefit from the “user in the loop” paradigm also in an indirect way: The higher awareness of energy consumption not only is expected to lead to better usage patterns, but also to increase the willingness to pay a premium for energy-efficient goods and services. These spillover effects (people who often deal with consumption information are more likely to consider environmental aspects when purchasing a new TV, or they tend to choose a car with an economic fuel usage) can help to realize additional saving potential.

The use of “smart” ICT for sustainability puts many other issues in the foreground. For example, integrating smart cooperating real-world objects into environments beyond energy management systems is an interesting field of research, which goes hand in hand with a growing number of Web interfaces and Internet-enabled devices around us. The development might accelerate the emergence of a so-called Internet of Things [27].

Security is another crucial issue. Smart meters for example, which often not only measure and communicate consumption values, but also have means to remotely reduce the load or to disconnect a household from the power grid, become critical infrastructure components. A virus provoking malfunction of the devices or a denial of service attack could lead to serious damage. Moreover, the electricity infrastructure is intended to be operated for a long time, but network security concepts and means (e.g., key lengths or encryption algorithms) – and the possibilities of attackers– can change at a much faster pace.

Usability and reliability are also important: Even people who are totally unfamiliar with computers or with network security now have a networked computer in the form of a smart meter in their home – rebooting it by hand, manually updating the device, or dealing with cryptic error codes is not an option.

Also, privacy concerns are often raised, especially in the context of smart metering. In fact, detailed knowledge of the use of electrical devices in a house may reveal much about the living habits of the occupants.20 Leaving most consumption data inside the house and only transferring data that is essential for billing might be part of the solution. This, however, rules out some interesting global optimizations and remote services that require detailed real-time energy consumption data. Also, convincing people to trust in the protective approach might turn out to be a challenge.

Since advanced metering makes fine-grained energy consumption data available, this raises the question how to exploit this data to develop valuable services that improve energy efficiency. A fact that has also lately attracted the attention of industry giants such as Google21 and Microsoft22, which might be on the way to become service providers (e.g., for automatic energy consulting) in the residential energy sector. For such services, data analytics and pattern recognition algorithms are essential, which might then help consumers to conserve energy (or at least to better understand their electricity bill…). The coalescence of the Internet of Things and energy topics will also foster the development of new product-as-a-service concepts, and give new stimuli to the adoption of home automation systems. It will thus also strengthen the interest in business service research

20 In their analysis [24], Lisovich and Wicker come to the conclusion that increased availability of data, along with emerging use cases, will inevitably create or exacerbate issues of privacy and that there exist strong motivations for entities involved in law enforcement, advertising, and criminal enterprises to collect and repurpose power consumption data.
21 Google Power Meter: www.google.org/powermeter
22 Microsoft Hohm: www.microsoft-hohm.com
in a sector that so far has limited experience in dealing with private users.

When it comes to influencing consumer behavior, further research is required not only to develop use interfaces that present consumption data in a suitable way, but also to identify and better understand concepts from behavioral science such as framing, goal setting, or identity signaling and their potential to induce a sustainable change. Moreover, it is important to identify engagement strategies (e.g., games, competitions, rewards) that help to further involve consumers once their initial curiosity is satisfied. For these purposes, ICT is not only an implementation means, but also a research tool that allows observing the effects of such measures in a timely and precise way.

Further research is also necessary to quantify or qualify attainable efficiency gains and energy savings by ICT usage. In an absolute setting, for example, it is difficult to determine how much energy smart metering can conserve. Reported results on pilot studies are only valid for the specific application domain, the technology under consideration, the user group, and other context conditions such as accompanying campaigns. Spillover and other indirect effects make an assessment even more difficult.

Indirect consequences of ICT on energy consumption are particularly difficult to analyze. On the negative side, one has to consider so-called rebound effects – a person with a fuel economic car, for example, might partly compensate the savings of the technology by simply driving more, because it is now cheaper. Some researchers even warn that there is some risk that ICT will become counterproductive with regard to general environmental sustainability or that it has only a low overall effect because positive and negative environmental impacts partially cancel each other out when aggregated [17]. An important increasing effect on energy consumption have for example ICT applications that make freight and passenger transport more efficient (i.e., cheaper or faster), because this creates more traffic and thus possibly induces more energy (i.e., fuel) consumption. In a thorough study on the rebound effect [43], Sorell concludes that this effect has generally been neglected when assessing the potential impact of energy efficiency policies. Analyzing and mitigating such opposing effects should therefore be a central effort of future research.

On the other hand, ICT has a large influence by enabling energy efficiencies in other sectors (logistics, transportation, building infrastructure, etc.). Buildings for example account for 40% of the EU’s energy requirements, and it is estimated that almost 35% of the energy used in the residential buildings sector could be saved by 2020 [8]. Some even expect that ICT’s potential to support other sectors to become more energy efficient could deliver greenhouse gas emission savings five times larger than ICT’s own footprint. Furthermore, ICT enables a shift from material goods to services and promotes a general structural change towards a less material-intensive economy. While the long-term consequences of dematerialization are difficult to predict, one can at least hope that in total it should have a beneficial effect on sustainability.

With all that, however, one must not forget that ICT has its own environmental footprint. ICT components do not only consume energy, but their fabrication and disposal is also an important factor to be taken into consideration. Also, the environmental effects of the laborious mining, processing, and usage of rare materials (such as tantalum, indium, niobium, etc.) to build the components must be considered. The advances in technology and its application should not detract us from the numerous problems with respect to obtaining and recycling the basic materials that are used to build ICT systems [16].

7. OUTLOOK – GREEN ICT FOR GREEN

Clearly, on the way to an economy based on sustainable energy, “ICT for green” calls for much work. Not only feedback systems as described above, but also large-scale distributed energy management systems that deal with huge amounts of event data and that operate in real time need to be developed, as are infrastructures such as electronic market platforms that support the cooperation of the various players and thus contribute to an automatic balancing of the highly fluctuating energy supply and demand. And of course, these systems have to be reliable, secure, and cost-effective.

Despite these and all the other challenges mentioned above, we are convinced that ICT, when used in a “smart” way, will help to significantly reduce our societies’ demand for carbon-based energy, while at the same time offering interesting business opportunities for industry and guaranteeing a desirable lifestyle for the citizens.

It should be clear that “green ICT” and “ICT for green” are no antagonists – both are important, and they complement each other [4]. The challenge for the future hence lies in the appealing synthesis “green ICT for green”.

8. REFERENCES


23 www.smart2020.org


