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

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## ABSTRACT
Information and communication technology (ICT) *consumes* energy, but is also an important means of *conserving* energy. Conventionally, it has done 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 more sustainable electricity generation. However, with the advent of "smart" technology from the field of ubiquitous computing, further ways of reducing growing levels of domestic energy consumption are now emerging. With this in mind, we discuss how getting consumers "into the loop" can achieve energy savings on top of the efficiency gains resulting from automated systems, and we describe a prototype application aimed at inducing 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 lives, but has also become 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 an increased use of natural resources. Even though for most countries energy consumption grew more slowly than gross domestic product, annual world-wide energy consumption increased steadily to reach 139,700 TWh in 2007, of which approximately 12% (16,429 TWh) was final electricity use [19].

While ICT with its favorable effect on the economy certainly has an important indirect impact on the overall use of natural resources and energy, the total energy consumption of ICT itself is difficult to estimate. Studies vary depending on the definition of ICT, the methodology used to generate the estimates, and the proportion of a device's energy consumption that is attributed to ICT. In a recent study published by the European Commission, the total electricity usage of the ICT sector (excluding consumer electronics) in the European Union (EU-27) was estimated to be 119 TWh in 2005, which corresponds to 4.3% of overall electricity consumption, or 0.6% of total energy consumption [8]. For the U.S., Laitner et al. [22] estimate that ICT's share of electricity consumption in 2008 was around 8%.

This percentage share of total electricity consumption by the ICT sector is certainly noteworthy. It warrants attention and calls for appropriate measures to be taken, particularly since it is increasing so rapidly – 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 incentives over and above environmental considerations ("*green ICT*"), such as the cost of running large data centers, challenges related to heat dissipation from processors, and the working lifetime of battery-operated devices.

However, high hopes also rest upon ICT to reduce resource and energy consumption in other economic sectors, and thus mitigate global warming. For example, ICT could help to improve the energy efficiency of established processes (i.e., increasing the ratio of a relevant target variable such as productivity or convenience to energy consumption), or it might be used to develop new concepts to generate, allocate, distribute, share, and use energy in a resource-efficient and environmentally-friendly way.

As environmental sustainability has become more important in recent years in parallel with rising energy costs, a growing number of large infrastructure systems and processes have been optimized to consume less power. With its general potential for large-scale simulation, optimization, and real-time control, ICT plays a leading role here. In a business context, ICT is also being used to make better decisions relating to resource and energy consumption – examples include optimizing production and supply chain processes [18], and developing environmental information systems [14]. Investments in energy-saving technologies often also pay off financially, particularly when energy costs are rising.

The *energy productivity indicator* (primary energy supply divided by 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 positively correlating the use of ICT to economic growth [42], there is strong evidence to suggest that ICT is an important driver for improving energy productivity. Laitner et al. estimate that in recent years, for each kilowatt of energy used by ICT equipment, approximately 10 kilowatts were saved economy-wide through productivity gains and efficiency improvements [22].

So ICT is a tool for enabling *energy efficiency* (typically as a side effect of process or infrastructure optimization), and has been for many years already. However, the recent slogan "*ICT for green*" also suggests that ICT is now being used more directly for *energy conservation* purposes. Examples include reducing commuting by teleworking and helping to save energy in the home. Since about one third[1] of all electricity is consumed by households, energy conservation is an important issue.

However, while industrial processes and public infrastructures still offer many opportunities for saving energy through conventional ICT-based automation and optimization, this is more difficult in a home environment. Conventional measures for reducing domestic energy consumption are limited – they essentially consist of using more energy-efficient appliances and reducing the energy lost by appliances on standby. Fortunately, however, ubiquitous computing technology (such as low-power sensors, cheap wireless communication, embedded Web servers, etc.) is now becoming available, offering new opportunities for saving energy, even without direct user involvement. Example scenarios include automatically detecting activity in the home [44] so that the heating or air conditioning can be adjusted accordingly, and a fridge that uses an "Internet of Things" [27] to communicate with a smart household electricity meter in order to use any cheap excess energy available on the power grid (for example, energy produced by intermittent renewable energy sources) to cool itself down to below its normal operating temperature (and thus store energy).

Although "ICT for green" alone will not save the planet, we believe that "smart" ICT can, when used consistently, reduce domestic electricity consumption by at least a few percentage points. In the rest of this paper we shall provide some arguments that support our belief. And in any case, the "greenest" form of electrical energy[2] is that which doesn't have to be produced in the first place because it isn't needed.

**Positioning and structure of this paper.** With respect to energy conservation and ICT, we are usually concerned with the issue of *"less energy for ever more computers"*. Instead, however, this paper will concentrate on the dual issue of *"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 following section. We will then discuss the potential for ICT to favorably modify consumer demand for energy. We outline how involving customers 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 obtain immediate feedback on household electricity consumption, and we describe a prototype application (the *eMeter*) that aims to change consumer behavior by providing that feedback. We conclude the paper with an itemization of important fields of future work.

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

The new role of ICT as a more direct enabler of sustainable development gives rise to a number of important challenges. These include questions such as how 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 establish new energy services and solutions, and how ICT can best contribute to smart energy marketplaces. The interest in new ICT solutions is mainly driven by a number of (partially interwoven) paradigm shifts within the energy sector, which we will 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 political pressure to decrease carbon dioxide emissions not only favors "green" energy, but also incites us to reduce energy consumption in general. Conserving energy is even becoming "chic" in some circles now, and ways of reducing energy consumption without decreasing standards of living are thus welcome.

**From regulation to deregulation.** Governments, particularly in Europe, have introduced a number of measures in recent years aimed at opening up 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, interactions across company borders are intensified. The rise of complex and timely interactions necessitates new ICT solutions, for example to avoid costly discontinuities in processes such as billing and to efficiently exchange the control information necessary to operate the electrical power grid. Deregulation is also leading to increased competition between players which, together with a growing demand for green products and services, is forcing companies to position themselves as green players. This is even leading to the promotion of "smart energy conservation products and services".[3]

**From centralized to distributed generation.** Local renewable energy generation, for example using solar panels on the roofs of buildings, is becoming more and more important. Excess energy that is not needed locally should be stored or fed into the grid. It is even conceivable that in the future the batteries of parked electric cars might act as energy buffers for transmitting power back into 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 levels of reliability) is a non-trivial issue that requires an appropriate information and communication infrastructure.

**From control to cooperation.** Traditionally, the electricity generated by power plants has had to match consumption at any given point in time. In the future, power-consuming devices will increasingly make the most of the energy that is currently available. More precisely, we would expect that, in a "smart grid", energy consuming appliances, energy generation units, power distribution units, and various other intermediaries would negotiate and cooperate to optimize their situation. For this to happen, suitable ICT-based market platforms would be required, which would then also

[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].

[3] Such as the energy efficiency software company OPOWER (www.opower.com) which helps utilities meet efficiency goals.

enable the creation of new forms of energy brokers or even virtual power plants [38] formed by small distributed generators such as combined heat and power (CHP) plants.

**From energy consumption to smart energy usage.** Many renewable energy sources are inferior to conventional power stations with regard to planning and controlling energy generation. Generation by wind turbines or photovoltaic systems in particular can lead to major fluctuations in the energy supplied to the power grid. Such fluctuations (and other allocation irregularities) sometimes even lead to negative energy prices.[4] This phenomenon can be mitigated by smart devices that consume or store energy when excess power is available, leading to an improved balancing of supply and demand (i.e., "demand follows generation" instead of "generation follows demand"). This not only requires an ICT infrastructure in which smart appliances can cooperate, but also measures such as smart meters, dynamic prices, and real-time forecasting and planning models that take account of various parameters such as the weather, the time of day and consumption habits.

Implementing these paradigm shifts is a major undertaking that will not only be costly and take many years, but must also be supported by the extensive use of "smart" ICT. Fortunately, recent advances in areas such as networking, embedded systems, construction automation, and ubiquitous computing can complement conventional ICT in this respect.

Although "smart" ICT can often operate in the background and conserve energy by optimizing and automating some processes even in households (which are typically complex and individualized environments), additional energy savings in such environments do require some consumer involvement. This represents a challenge, since human interaction is typically regarded as inconvenient, and saving energy is often seen as more of a necessary constraint than a key objective. Nevertheless, providing consumers with feedback on the energy consumption of their various activities and appliances should motivate some of them to change their habits and thus help to save energy. We will discuss this issue and appropriate concepts and technologies in more detail in the following sections.

## 3. USING ICT TO INDUCE BEHAVIORAL CHANGE

While automation and energy-optimized systems will doubtless be essential for achieving savings, the adoption of these systems and user behavior in general will have a major influence on the demand for energy. ICT can play an important role here because it can assist individuals in making more informed decisions and reward socially desirable behavior in daily life. In fact, getting users into the loop can not only help to guide individuals when using energy consuming devices, but also encourage them to make favorable decisions, e.g. when purchasing electrical devices, heating systems, and energy-efficient family cars.

There are many situations in which 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 PC and imaging equipment has automated power-saving features that switch screens or CPUs to low-power mode after a period of user inactivity. These features, however, are all too often not activated in either home or office environments, even though 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]. One amazing example of unanticipated growth in energy demand is that of the market success of coffeemakers (in particular small espresso machines) in Swiss households and offices. For convenience, these machines often keep the water or beverage hot or even preheat 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 using kitchen hobs, ovens, microwaves, and similar cooking appliances (including coffeemakers!) in the same country [33], the additional demand is enormous and went virtually unnoticed or at least was not attributed to the device by most owners.

Reasons for lost saving potential originate at least in part from a lack of knowledge on personal energy consumption, the difficulties people have in investigating the efficiency of their equipment, and a rather limited motivation to modify their personal behavior. In order to mitigate these deficiencies, the European Union initiated an *Action Plan for Energy Efficiency*[5] in 2006 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" [4].

In this context, high hopes are placed on smart metering infrastructures that provide real-time information flows and enhanced ways of managing and controlling household energy consumption. However, a meta study of 64 pilot projects we conducted to better understand the efficiency gains generated by smart metering and monthly billing showed a rather gloomy picture of the saving potential achieved. After eliminating studies that had methodological weaknesses and low explanatory power[6], the meta study showed energy savings of just 1 to 2 percent. 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 worth noting that many participants in the pilot projects were reluctant to have the metering technology installed. A rapid decline in involvement was also common shortly after the devices were introduced, and sustainable behavioral changes were only achieved within a small subgroup. One could therefore conclude that, while many people claim that saving energy is important, their willingness to act accordingly is rather limited [39]. But the situation is not that hopeless. A closer look at those particular pilot studies that used advanced motivational cues (beyond promising future cost savings) shows they 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 for inducing behavioral change. These measures can be categorized into two groups, one supporting rational behavior (informational support), and the other leveraging somewhat irrational

[4] For example, on the European Energy Exchange (EEX), hour contracts showed a price of -500.02 Euro/MWh for hour 2-3 on Oct. 4, 2009.

[5] http://ec.europa.eu/energy/action_plan_energy_efficiency/doc/com_2006_0545_en.pdf

[6] E.g., observations that only lasted less than two months, contained no control group, were accompanied by other efficiency measures (such as high-profile personal energy consulting campaigns), or which included only a priori interested participants.

motivators (intrinsic motivation and social positioning). Both categories are outlined below.

**Informational support.** It is widely accepted that communicating consumption data in the form of a mere value and physical unit is not adequate for most people [26]. For a more thorough interpretation, analogies are regarded as helpful, and can also increase the timescales over which users reflect and process the information. The type of analogy must be chosen carefully however, to guide the user in the desired direction, e.g. specifying the size of solar panel that is required to produce an energy equivalent, for example, manifests the feeling that the amount of energy is large; mentioning the number of cups of tea that could be prepared using this energy has the opposite effect.

**Table 1. Efficiency gains reported in feedback studies**

| Project lead & country | House-holds | Energy savings | Source |
|---|---|---|---|
| Mountain, Canada | 505 | 6.5% against baseline over 2.5 years. Adjusted for weather & demographics. | [30] |
| SydEnergy, SEAS-NVE, Denmark | 677 | 2-3% electricity savings. Significant at 5% and 10% level. | ESMA, Togeby[7] |
| Arvola, Finland | 525 | 3% against controls in 2 year study for feedback; 5% for feedback & advices. | [1] |
| Henryson, Scandinavia | 600-1500 | Between 0% and 12%. | [15] |
| Government, Sweden | 6 millions | Approximately 3%. | ESMA, WP2D6[8] |
| Nielsen, Denmark | ~1500 | 1% in flats, 10% in houses. | [11], [31] |
| Hydro One, Canada | 500 | Between 7% and 10%. | ESMA, WP2D7[8] |
| Wilhite/Ling, Norway | ~1000 | 10% against controls over 3 years. | [6], [47] |

Another important way to help place personal consumption in a wider context is by making comparisons with other entities (families, homes, etc.). Care must be taken when choosing average values – showing individuals that they perform better than average regularly leads to a reduction in effort and ultimately to higher energy demand. The same effect occurs when recipients are confronted with average values that are much better than their own performance, as they often perceive the goal as being too difficult to achieve and therefore not worth pursuing [41].

When provided appropriately, informational support increases the willingness to act. In order to transform the momentum into change, 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 on the importance of their personal engagement, they often lack motivation to ultimately take action. Established consumer research and marketing concepts appear to be promising ways of increasing intrinsic user motivation to achieve goals such as conserving energy. These 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 increased persistence. Important influencing variables include attainability and self-efficacy, and also 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 [25]. The degree of ambition can be positively influenced by providing appropriate defaults or by stating that attachment figures or authorities have made a specific selection. Energy monitors, for example, can combine defaults, goal setting, and feedback on the state of current performance, while providing advice on ways of achieving objectives.

*Energy budgets* appear to be a good method of increasing intrinsic motivation. In a British pilot project, pre-paid electricity tariffs with simple interfaces to keep track of the current balance positively influenced saving efforts [7].

*Comparisons* with other entities have already been outlined as informational cues. They are especially effective when the selected peer is similar to the recipient of the information, lives in close proximity (e.g., the same village), has the same profession, or is a member of a familiar or admired group [29]. Moreover, people tend to act in a socially preferable way when their behavior becomes visible to others. Initial projects are using social networks such as twitter and facebook as a platform for energy efficiency activities, but have not yet gained much attention.[8]

"Smart" ICT makes it possible to combine informational support and ways of fostering intrinsic motivation. In an ideal scenario, the deployment of energy measurement devices and energy conservation services would be embedded within a wider campaign, game, or competition to get users involved. Lotteries have proved to be efficient as an initial motivator[9], but other incentives that can be easily facilitated using ICT have not yet been tested on a larger scale.

We will describe a prototype system and demonstrator (the *eMeter*) for testing and evaluating 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

Several energy monitoring solutions already exist that can provide feedback on electricity consumption. They aim to help users 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 are primarily limited to displaying the aggregated consumption of a circuit or even the entire power demand of a household. There are several products available, such as Wattson[10], Onzo[11], Current Cost[12], Power Cost Monitor[13], and TED-1000[14]. Once installed, they visualize the overall electricity consumption on a display unit. However, installation at a circuit or household level is complex and users are therefore often discouraged from using such products. Furthermore, these solutions suffer from the fact that,

[7] http://ea-energianalyse.dk/publications_uk.html

[8] E.g., Energy Monsters, www.facebook.com/home.php?#/apps/application.php?id=102704939189&ref=appd

[9] A successful campaign has been launched by the utility SEAS-NVE, see www.maalerjagten.dk

[10] DIY Kyoto, www.diykyoto.com/uk/wattson/about

[11] Onzo Ltd., www.onzo.co.uk

[12] Current Cost, www.currentcost.com

[13] Blue Line Innovations Inc., www.bluelineinnovations.com

[14] Energy Inc., www.theenergydetective.com

mainly for safety reasons, the wiring around household meters is inaccessible in many countries and modifications require a technician. Another drawback is that they are unsuitable for providing users with feedback on the consumption of individual devices which, from a feedback perspective, would be necessary to draw conclusions on how consumption and behavior relate to each other.

Some experimental systems attempt to disaggregate the total consumption measured by a single sensor to provide more specific information about electricity consumption at device level [28]. The aim of these non-intrusive load monitoring systems is to keep equipment costs and installation effort to a minimum, but still obtain detailed energy usage data. To determine which appliances are currently running, some of these systems simply measure the overall power difference from one point in time to the next; a principle that has been investigated by several researchers in the past [2], [9], [37]. Other more sophisticated approaches use statistical signature analysis and pattern detection algorithms to infer the devices in question from the current and voltage wave forms [23]. To achieve disaggregation, these systems require either a priori knowledge about the household devices and their electrical characteristics, or entail a complex calibration and training phase involving the user, in which the system learns about specific device characteristics. However, a priori knowledge is difficult to obtain in a world of fast-changing small appliances, and manual training is a significant barrier to usage. Furthermore, appliances whose power consumption varies or overlaps with that of other devices pose a particular challenge for 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 on a domestic electric circuit. On the residential power line, it listens for unique noise changes caused by the abrupt switching of devices. This approach makes it possible to determine, with some probability, 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 subdivided into direct and indirect systems. Direct systems require an in-line sensor to be installed for every device or circuit. Indirect sensing systems use a central electricity meter together with additional context sensors to monitor energy consumption.

*Direct sensing systems* mostly come in the form of smart power outlets. They are relatively easy to deploy and several products exist[15]. Once installed, they measure the attached load and display the measurement data on the unit itself or transmit it wirelessly to a remote display. However, these systems are not able to aggregate consumption from multiple sensors and combine the different data to form a comprehensive picture.

To overcome this limitation, other work has focused on developing systems that combine multiple power sensors. Guinard et al. [13] realized a system that integrates smart power sockets (“Ploggs”[16]) which communicate their measurements via Bluetooth or Zigbee. A gateway is responsible for identifying smart sockets that are within range. It also makes their functionality available as resources on the Web and provides local aggregation of device-level services (e.g., the accumulated consumption of all sockets). Jiang et al. [20] developed a system where sensors measure power consumption at outlets and communicate their readings 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 a house quickly becomes expensive. *Indirect sensing systems* try to remedy this by keeping intrusion into 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 a household together with additional context sensors (such as light, sound, and electromagnetic sensors) 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. However, the system’s performance depends greatly on the correct calibration and placement of the distributed context sensors, 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 various electricity feedback systems. Single sensor systems are hard to deploy but reasonably priced, and once installed they have a low usage barrier. Since the single sensor is typically installed close to the household meter or in the fuse box, overall consumption is easy to monitor. However, to obtain information at device level calls for more sophisticated approaches that require algorithms to be calibrated. In addition, due to the wide variety of electrical devices involved, the accuracy of these systems is somewhat limited.

**Table 2. Properties of different energy monitoring solutions**

| Characteristics | Single sensor | Multiple sensors | |
|---|---|---|---|
| | | Direct in-line | Indirect |
| Installation | Hard | Medium | Hard |
| Cost | Low | High | High |
| Usage barrier | Low | High | High |
| Calibration | Hard | Easy | Hard |
| Device level accuracy | Low | High | Medium |
| Household level accuracy | High | Low | High |

In contrast, direct in-line electricity monitoring systems are very accurate at device level since the electricity is measured at the device itself. However, this advantage comes at a 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 large number of sensors or smart power outlets throughout the house. Therefore such systems will typically only cover a subset of all electricity consuming devices in a household.

Finally, indirect systems are theoretically able to provide feedback both on overall electricity consumption and, to a certain extent, on device-level electricity usage. However, they require users to deploy various context sensors in the right places and necessitate complex calibration, which leads to both high costs and a high usage barrier.

The way forward for electricity monitoring systems involves a scenario in which household appliances, which today have only

[15] For example “Kill a Watt”, www.p3international.com/products/special/P4400/P4400-CE.htm

[16] Plogg, www.plogginternational.com

limited capabilities, become more powerful and smart. Through the integration of small, inexpensive 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 an established protocol (e.g., powerline, Zigbee, WLAN), although dedicated new technologies such as digitalSTROM[17], rivaling traditional domestic network technologies (BACnet, EIB, KNX, etc.), might also feature.

Moreover, the cost of integrating embedded Web servers (based on REST and IPv6 / 6LowPAN) into household appliances should in future be low. This would lead to a wide variety of application scenarios in which the smart domestic electricity meter (or a similar device) could serve as a central component for data aggregation and analysis. At the same time, embedding a Web interface into appliances would enable them to be fully integrated into the Internet [13]. As well as the allocation of a device-specific Web page for status information, this would allow the device to be controlled and its data to be processed using the full power of Web 2.0 tools, giving rise to a "Web of Things" [12]. It is obvious, however, that with such possibilities we would need to pay serious 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 attempts 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

- feature a low usage barrier,
- be presented on a device that is already integrated into users' daily life,
- be given frequently, in real time, and be available when needed, and
- provide the ability to apportion total electricity consumption.

The eMeter system considers these issues. It achieves a low usage barrier by using a smart electricity meter, which is going to be installed in households throughout Europe by law anyhow. So all that users have to do is install a mobile phone application that can easily be downloaded from the Internet. The system is simple to setup and requires no modification by the user – neither to the electrical wiring, nor by deploying additional hardware at device level [46].

By providing real-time feedback on a mobile phone, the system features not only feedback on a device that is already part of the user's life, but also the ability to provide instantaneous feedback that is available when needed. This is especially important since trials have shown that when using an additional battery-powered display for electricity feedback, 50% of all 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. Since they are not integrated into users' daily life, these additional displays do not seem capable of motivating users for long periods of time.

Lastly, useful feedback has to link specific actions to their effects by providing the ability to disaggregate overall electricity consumption. In order to take effective measures, it is vital to understand how much power individual devices consume in standby mode or while

[17] www.digitalstrom.org

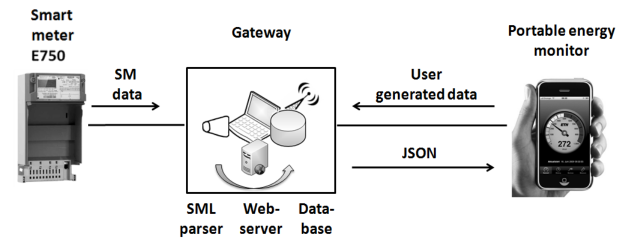


**Figure 1. Smart meter communicating with the mobile UI**

operating [36]. The eMeter's interactive measurement functionality allows users to measure the 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 domestic load; 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 energy consumption and enables 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 physical resources to be easily and seamlessly integrated into the Web. For this purpose, REST proposes two basic principles. First, transferring the conventional 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. In contrast to traditional electricity meters, the 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 asking the meter to transmit all available data via its interface every second.

The *second component*, a lightweight gateway, is implemented in Java and consists of a parser, a database, and a small Web server (based on the RECESS![18] framework). In order to continuously acquire the logged data from the smart meter in near real time, the integrated SML[19] parser automatically polls the meter every second and stores the data it receives in an SQL database. Access to the gateway's functionality and 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 implements the four basic HTTP verbs. This is a powerful concept since it allows the meter data to be accessed via any Web browser. For example, just by calling

*http://serverAddress]/emeter/energyServer/ smartMeter/1/measurements.json?c=last*

[18] www.recessframework.org

[19] Smart Message Language, www.t-l-z.org/docs/SML_080711_102_eng.pdf

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 the form of an HTTP or JSON message as shown below.


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


Since 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 implemented using Objective-C. It exploits the functionality provided by the gateway to access the meter readings and dynamically visualize the information in real time. It does this by calling appropriate URLs on the gateway together with the corresponding HTTP verb, and processing the JSON message it receives in response. The user interface is also responsible for transmitting user-generated data, such as details about the household and appliances, to the gateway.

The architecture we have 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 detailed, real-time feedback. It also shows that directly integrating smart physical objects into the Web infrastructure greatly facilitates 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 current electricity consumption (a), a historical view of energy consumption (b, c), a device inventory view that displays energy usage and costs per measured device (d), and a measurement view (e) which enables the user to interactively measure the consumption of almost any switchable electrical appliance in the house.

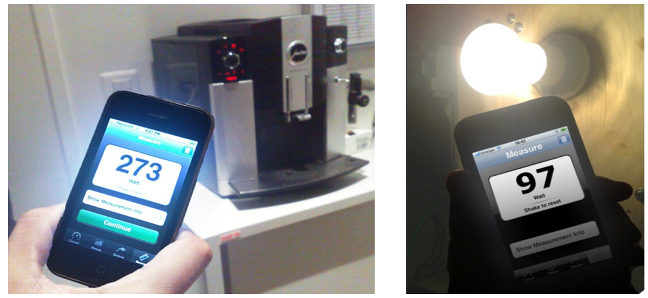


**Figure 2. User measuring the power consumption of devices**

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

The *history view* (Figure 3b, 3c) shows a line chart of historical consumption. Users can choose between different time periods, e.g. previous hour, previous day, etc. Together with the chart, this view displays 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 historical consumption to that of a typical average household of the same size in the same location. The historical 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 view 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 also enables users to sort the readings by location or the amount of power used, so that the biggest energy guzzler appears at the top.

The *measurement view* (Figure 3e) enables users to interactively measure the electricity consumption of most switchable appliances in the household. To perform a measurement, the user simply activates the process by pressing the green start button and then turns the device being 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 – as soon as 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 significant change in this value. It then calculates the difference between the


a b c d e

**Figure 3. eMeter user interface (from left to right):**
**current consumption view, history view (aggreg. consumption), history view (budgeting), device inventory view, measurement view**

two values. (Incidentally, if another device is switched on or off during the measurement interval, the result may be incorrect. However, because this generates a spurious reading, users are typically aware of the situation and can simply repeat the process.)

After the measurement has been carried out, users can save the measured device to a list of appliances. The user interface provides additional options for personalization. For example, users can take photos of the measured appliance, or detail its utilization to calculate the annual costs incurred. If 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 at a household and device level. The system attempts to overcome the discouraging installation overheads incurred by other typical energy feedback systems by making use of a smart electricity meter, whose installation is becoming mandatory in Europe and which provides highly accurate readings at a household level. Assuming that the lightweight gateway component will in future 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 – something that can be done easily in minutes or even seconds. Since the system requires no additional hardware, it is inexpensive and should generally have a low usage barrier.

The system's accuracy at device level, however, suffers from its single sensor approach. We are trying to overcome this by integrating into the user interface measurement functionality aimed at providing users with an initial idea of how much energy different devices consume. Provided the brief measurement interval is representative, it enables users to measure the consumption of any switchable or pluggable device. The only real challenge might be that of correctly measuring devices whose energy consumption is variable or dynamic (such as laptops). However, some household devices that consume a non-negligible amount of energy, such as washing machines and freezers, cannot usually 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 through autonomous optimization and by inducing changes in user behavior. But achieving the latter is not that easy. Bearing in mind the somewhat disappointing results from early feedback systems using smart metering infrastructures, one could indeed question how effective getting the "user into the loop" really is. However, the rather unsatisfactory results seem in the most part to be a consequence of insufficient ways of motivating and engaging consumers, as notable efficiency gains have been demonstrated in many of the better organized settings (see Table 1).

Even if the direct savings generated by feedback systems are only in the order of a few percent, the cheapest and most environmentally-friendly type of energy is still that which is not produced in the first place because it is not needed. Moreover, society should also benefit indirectly from the "user in the loop" paradigm. A raised awareness of energy consumption is not only expected to lead to improved usage patterns, but also to an increased willingness to pay a premium for energy-efficient goods and services. These spillover effects (people who frequently deal with consumption information are more likely to consider environmental aspects when purchasing a new TV, and are likely to choose an energy-efficient car) can help to achieve additional savings.

The use of "smart" ICT for sustainability brings many other issues to the fore. For example, integrating smart cooperating real-world objects into environments other than energy management systems is an interesting field of research, which goes hand in hand with the growing number of Web interfaces and Internet-enabled devices around us. This 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 readings but are also able to remotely reduce the load or disconnect households from the power grid, become critical infrastructure components. A virus that caused devices to malfunction or a denial of service attack could lead to serious damage. Moreover, the electricity infrastructure is intended to be a long-term undertaking, but network security concepts and methods such as key lengths and encryption algorithms – and the possibilities open to attackers – change at a much faster pace.

Usability and reliability are also important. Even people who are totally unfamiliar with computers or network security now have a networked computer in their home in the form of a smart meter – 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 a household's electrical device usage may reveal much about the habits of its occupants.[20] Leaving most consumption data inside the house and only transferring data that is essential for billing might be part of the solution. However, this 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 of how to exploit this data to develop valuable services that improve energy efficiency. This issue has also recently attracted the attention of industry giants such as Google[21] and Microsoft[22], who might be on their way to becoming service providers (e.g., for automatic energy consulting) in the residential energy sector. Data analytics and pattern recognition algorithms are essential for such services, and might then help consumers to conserve energy (or at least understand their electricity bills better…).

The coalescence of the Internet of Things and energy topics will also promote the development of new product-as-a-service concepts, and provide new stimuli for adopting home automation systems. It will thus also strengthen interest in business service research 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 user interfaces that present con-

[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 are 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

sumption data in a suitable way, but also to identify and better understand concepts from behavioral science such as framing, goal setting, and identity signaling and their potential to induce sustainable change. Moreover, it is important to identify engagement strategies (e.g., games, competitions, and rewards) that help to boost consumer involvement once their initial curiosity has been satisfied. For these purposes, ICT is not only a means of implementation, but also a research tool that allows the effects of such measures to be observed in a timely and precise way.

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

ICT's indirect consequences on energy consumption are particularly difficult to analyze. On the negative side, one has to consider so-called rebound effects – someone with an energy-efficient car, for example, might partly compensate for the savings achieved by technology by simply driving more, because it is now cheaper. Some researchers are even warning 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]. For example, one important factor relating to *increased* energy consumption is demonstrated by 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 focal point of future research.

On the other hand, ICT exerts a major influence by enabling energy efficiencies in other sectors (such as logistics, transportation, and building infrastructure). 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 help other sectors become more energy efficient could deliver greenhouse gas emission savings five times greater than ICT's own footprint[23]. 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 not only consume energy, but their fabrication and disposal is also an important factor to be taken into consideration. The environmental effects of the laborious mining, processing, and usage of rare materials (such as tantalum, indium, niobium, etc.) to build these components must also be considered. Advances in technology and its application should not detract us from the numerous problems relating to obtaining and recycling the basic materials that are used to construct ICT systems [16].

[23] www.smart2020.org

# 7. OUTLOOK – GREEN ICT FOR GREEN

Clearly, if we are to achieve an economy based on sustainable energy, "ICT for green" is still in need of much work. We need to develop not only feedback systems as described above, but also large-scale distributed energy management systems that can deal with huge amounts of event data and operate in real time, as well as infrastructures such as electronic market platforms that support the cooperation of various players and thus help to automatically balance 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 significantly help to reduce society's 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 not mutually exclusive – both are important, and they complement each other [5]. Hence the challenge for the future lies in the appealing synthesis "green ICT for green".

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