Mechatronics to drive environmental sustainability: measuring, visualizing and transforming consumer patterns on a large scale

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***Abstract*— In order to reduce our society's dependence on fossil fuels, the energy sector has started to undergo massive changes. Information and communications technology (ICT) increasingly plays a key role in this transformation, both on the supply and demand side. While 85% of the residential energy in the DACH region is consumed by space and water heating, the vast majority of work in the energy informatics field does not focus on these two critical end uses. And yet, the discipline could contribute greatly to reducing consumption and emissions in this area – often with a close nexus to electricity. Besides, direct, real-time feedback on hot water consumption has a particularly high savings potential and can further broaden the sphere of impact of the energy informatics discipline. This paper describes a self-powered energy and water meter that provides users with such feedback in the shower. After an earlier proof of concept study with 60 households together with the Swiss Federal Office of Energy that yielded average energy and water savings of 22%, the smart shower meter has been developed into a mass-market compatible application that has been installed in 8,000 households. This was accompanied by a study with 700 households to verify its practical viability, consumer engagement, and effectiveness in the field. The device showcases a practical example of how ICT applications can be successfully implemented at scale to transform consumption patterns in emission-intense domains, also beyond electricity.**

Keywords—water-energy nexus, energy-aware appliances, direct & real-time feedback, residential energy consumption, consumer engagement

I. MOTIVATION

Policy makers have put forward ambitious goals to reduce our society's dependence on fossil fuels and to lower the related carbon emissions. By now, many of these visions have been translated into actual policy guidelines. Prominent examples include the 2,000-Watt-society with its pilot regions Basel, Zurich, and Geneva (compared to current levels of 6,000 W in Western Europe and 12,000 W in the U.S.) as well as the 20-20-20 targets of the European Union, whose key objectives for 2020 aim at a 20% reduction in EU greenhouse gas emissions (from 1990 levels), a 20% share of renewable energy sources, and a 20% improvement in energy efficiency. In order to attain these goals, both the energy supply and demand side have started to undergo massive changes, and a timely decarburization of the energy production must go hand in hand with much higher energy efficiency gains than at the current rate of improvement [1]. This implies not only a large-scale adoption of more efficient technology and an integration of renewable energy resources, but also requires behavioral changes and increased awareness of the carbon footprint of our daily actions.

Information and communications technology (ICT) plays a pivotal role in this transformation on different system levels. As [2] described in a Nature article, ICT interacts with environmental issues on four levels: (1) the physical level, with the environmental impact of physical infrastructure and devices (manufacturing, operation and disposal), (2) the application level, as a vector to reduce environmental impacts, e.g., smart meters, smart buildings, or optimized manufacturing, (3) through its effects on economic growth and shifts of consumption patterns and finally, (4) through systemic effects on technology convergence and society at large. Over the past years, the ICT industry has actively supported and driven sustainable economic development. As a result, energy informatics (EI) has emerged as a new discipline [3] to advance the application of computer science and engineering in domains that are relevant to the energy sector.

With the residential sector accounting for 25% of our society's energy consumption [4] – not even including the large amount of "grey energy" embodied in consumer products and food that is ultimately determined by consumer choice – EI-researchers and policy makers have identified households as a "huge reservoir of potential for reducing carbon emissions and mitigating climate change that can be tapped much more quickly and directly" [5] than carbon emissions trading, fuel economy standards or changes on the energy supply side.

In this highly relevant household sector, the effort to build systems that are specifically targeted at electricity supply and demand seems to dominate the focus of the EI discipline. Over the past years, multiple projects and programs have been set up to address the related interdisciplinary challenges. The vast majority of the endeavors focus on smart grid applications in general and data generated by electricity smart meters in particular. This is mainly due to the large number of electricity smart meters that have already been deployed; national and European policy has made electricity data collection mandatory at least on a monthly basis. Research efforts on electricity smart meters as enablers for behavior change are also driven by the growing share of intermittent renewables on the supply side and the advent of electric vehicles: both increase the pressure for more flexible electricity demand, in particular for load shifting and peak clipping. Moreover, the now available data generate vast opportunities for the development of new tariff schemes, data mining related services, and the like.

While there is no doubt that the focus on electricity offers ample opportunities for the application of ICT to improve efficiency and integration of renewable energy sources, there is also no dissent that energy consumption and carbon emissions in the residential sector are by far dominated by the use of fossil fuels for space and water heating. In the DACH region, 85% of the residential energy are consumed by space and water heating [6], [7]. Yet, these emission-intense domains have received relatively little attention, and especially water heating has been disproportionally neglected by information technology. This is mainly due to two factors: ICT power supply and awareness. As for the first, ICT applications are typically powered directly by batteries or mains electricity. While the first requires periodic replacements, the deployment of electric devices in wet or humid environments is prone to quality problems. Moreover, plumbers are often not willing to install line-powered devices in close proximity to water or lack the required certification and thus impede their adoption. Second, the general public does not associate water consumption with energy, and increased water conservation efforts in the DACH region have recently been qualified as "absurd" in several media reports as (cold) water is abundant [8]. This misconception is problematic. First of all, water heating is the second largest energy end use in Europe [7] only after space heating, accounting for 13% of the electricity consumption in Swiss households [9] and for 6% and 7%, resp. of Europe's total energy usage and CO2 emissions ([10]). Between 84% and 97% of water-related energy are ascribed to water heating ([11], [12] and [13]), with the largest share being used in the shower. Second, today's interdependencies between water and energy are increasing: yet the water-energy nexus is not limited to the macro-level (in terms of electric power generation and water treatment), but increasingly also affects household applications: solar thermal collectors and micro combined heat and power systems are only two prominent examples for this trend. The general public poorly understands these interrelations, and good opportunities for energy conservation are missed. By now, most people are sensitized to simple environmental actions such as switching off lights when leaving a room; while highly visible, the environmental impact of these actions is rather limited (lighting typically accounts for 6% of household end-use energy [14]). On the other hand, hot water conservation hardly comes to people's mind as a means to reduce energy consumption. Yet, hot water usage is an ideal area for consumption feedback systems: first of all, hot water is only withdrawn from limited number of points in the household, with showers accounting for the majority of residential hot water demand. As a consequence, concrete, instantaneous and actionable consumption feedback can be provided right at the point of consumption. While the feedback on electricity consumption tends to be more complex, subject to base-load consumption and the interference of other household members, users have a high level of control of their hot water usage, and the impact of actions is immediately visible.

Social sciences have uncovered successful communication strategies for behavior change and public engagement. Recently, academics, companies, and policy makers have come to place high hopes on the application of these insights in today's technologies to serve as a basis for better-informed consumer decisions and successfully appeal to socially desirable behavior of individuals. A number of programs have proven the feasibility and cost-effectiveness of green ICT to reduce residential energy consumption in particular. As [15] stated, "What has been missing is a concerted effort by researchers, policy-makers, and businesses to do the "engineering" work of translating behavioral science insights into scaled interventions, moving continuously from the laboratory to the field to practice. It appears that such an effort would have high economic returns".

This said, the paper at hand aims at making three contributions to the Energy Informatics domain:

- First, it provides insight into the design of an energy-autarkic, micro-mechatronic device that offers in-situ consumption feedback on hot water usage. The technology may, in future applications, grow together with combined power-heat systems and related energy information systems.
- Second, it shows the effects of an easy-to-deploy, low-price, and truly mass-market compatible application that can considerably contribute to the reduction of carbon emissions and energy consumption. Besides, an accompanying large-scale field study aims to provide insights that can be applied to many other feedback technologies.
- Third, the work is meant to strengthen the vision of the Energy Informatics domain as a powerful means to contribute also to domains beyond electricity.

The following section provides an overview of related work. Section 3 describes the operation and technical characteristics of the device and its field deployment. It is followed by a concluding outlook on the concrete implications of its deployment. The paper concludes with a broader perspective on the potential contributions of the energy informatics discipline.

II. LITERATURE

This section gives an overview of related work on large-scale eco-feedback studies using ICT, followed by existing solutions in the water consumption domain.

A. ICT for sustainability: large-scale behavior change trials

Over the past years, several studies demonstrated the potential of ICT artifacts both to promote environmental sustainability and to carry out theory-driven field experiments at scale: [16] examined the impact of an online intervention on college students' driving behavior. [17] examined the effects of positive and negative social sanctions on energy demand and engagement with an online community. The same experimental platform was used to identify individuals' preferences towards sustainable energy consumption using a public-goods game [18]. [19] investigated the influence of descriptive and injunctive social norms in a field study. The authors found no difference with respect to frequency of system usage.

Meta-studies that evaluated the impact of consumption feedback delivered via technology report effects from none to 20 percent energy savings ([20], [21]), yet with very heterogeneous results. [22] attribute this heterogeneity to three main factors: a) different research designs (size, participant selection procedures, duration, and evaluation methods), b) features of the feedback technology (timeliness, data display, interactivity, sociability, and controllability) and c) differences in the participating population (self-selection bias). Technology features that were identified as relevant by meta-studies include frequency, duration, timeliness, content, breakdown, medium and way of presentation, and comparisons ([21], [23], [24]). [25] points out that the relevance of psychological and psychosocial variables is behavior specific and higher for behaviors that are not strongly constrained. This implies a particularly large potential for behavioral interventions in highly discretionary behaviors such as showering.

B. *Existing feedback solutions for hot water consumption*

The majority of research on ICT applications that target (hot) water consumption have not yet overcome prototype status and their deployment is limited to a handful of households or exploratory studies. [26] performed evaluations of water eco-feedback displays. Based on exploratory surveys with 651 respondents and semi-structured in-home interviews with ten families, participants' initial reactions to different forms of feedback information were assessed. The study found a strong preference for specific, detailed information on water usage at the individual fixture level, for a breakdown by hot/cold, and for comparing data for contextualization. The study, however, was limited to hypothetic intention-to-use questions and did not report real-world usage data.

Research papers that describe real ICT artifacts to promote sustainable hot water consumption concentrate on establishing a proof of concept. Existing solutions can generally be categorized into two areas based on their type of data collection: (a) residence-level monitoring and (b) distributed or single-fixture sensing. Projects on the residence level include [27] and [28], both using accelerometers mounted on the pipes to infer flow rates. Both projects, however, did not overcome practical problems prohibiting the application in the field (precision issues and a high sensitivity to the specifics of the infrastructure and configuration). [29] describe "HydroSense", a low-cost pressure-based sensor that automatically determines water usage activity and the flow from a single installation point. Identification of water fixtures is based on the unique pressure waves that propagate to the sensor. However, the proposed approach requires an external power source. Moreover, the technique requires a time-consuming and sophisticated learning phase whenever the infrastructure is changed (e.g., new shower head in the shower, new washing machine). While interesting from an academic perspective, it cannot be foreseen when and how the challenges of applying the results at a commercial scale can be overcome.

Examples for single-fixture sensing include either mechanical flow meters or microphones. The major drawback of all these solutions comes from their power requirements and, in the case of microphone solutions, the need for calibrating. [30] introduced "Waterbot", a system to change water consumption behavior at the sink. [31] developed "UpStream", a pervasive display for showers and sinks using microphones for sensing; [32] describes an ambient shower display named "show-me". [33] designed "Shower Calendar", another pervasive concept study to motivate shower water savings. While that concept study describes an innovative design and information visualization approach, the system requires an array of electronic equipment (a flow meter, a micro-controller board, a number pad, a computer, and a screen) placed next to the shower, prohibiting permanent or larger-scale application. A recent Australian study [34] incorporated a larger number of households to assess baseline household water consumption (N=151) and to evaluate the effectiveness of a shower feedback device (N=44). The focus of the study, however, was on the baseline measurement results and on the effects of the intervention, not on the monitoring and data collection method. The study used slightly modified commercial pulse water meters and data loggers; given their price point, their scale of residential deployment - beyond research studies - is limited.

III. DEVICE DESCRIPTION

We developed a micro-mechatronic, energy autarkic water and heat meter that provides direct feedback on the energy and water consumption in the shower. The device measures and calculates detailed consumption variables (flow rate, water volume and temperature, energy, and energy efficiency class) and displays direct feedback on the ongoing shower event. The device can store time series data of 507 shower events.

A. *Operation*

The installation requires no tools or skills and can be carried out by the users. The device is mounted between the hose and the handheld showerhead, a location that facilitates and elicits periodic user glances during the shower process. Users receive direct feedback on the current water temperature [in °C], water volume used [in liters], energy [in (k)Wh] and an energy efficiency rating.

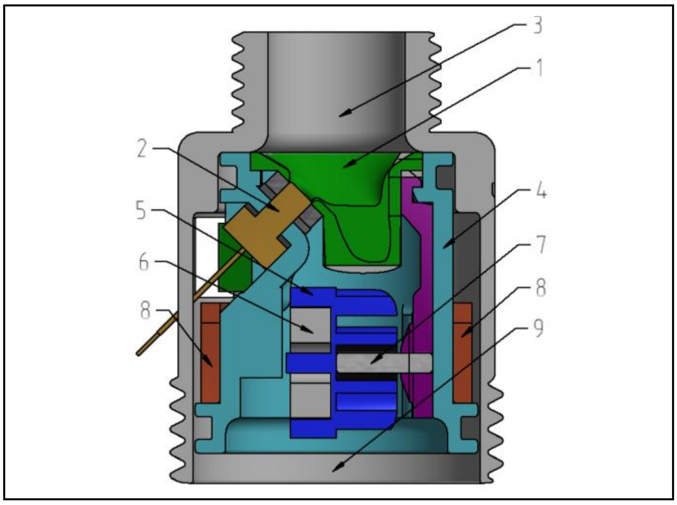

Figure 1: Cross section of the micro-generator unit: 1- turbine nozzle; 2 - thermistor; 3 – measurement unit water inlet; 4 – micro-generator tube; 5 – turbine wheel; 6 – generator magnet; 7 – generator wheel axle; 8 – generator coil; 9 – measurement unit water outlet

The device is the successor to the prototype version described in [35]. Both models were developed in collaboration with the Swiss company Amphiro AG, a spin-off of ETH Zurich. In contrast to its predecessor that used a battery-powered display, the device is energy-autarkic. A built-in micro-generator harvests energy from the water flow, supplying the device with the power required for its processing unit and display. This eliminates the need for periodic battery recharging by the users, hence addressing one of the most prevalent risk for operation failure. This enables tracking user behavior over extended periods of time. The device starts measuring, calculating and providing feedback as soon as water drives the generator. The generator serves two purposes: it measures the water flow through its angular frequency and it powers the electronics. Since the smart meter harvests its energy from the water flow, all electrical components are optimized for intermittent energy supply (e.g., low-power microcontroller). Voltage preconditioning is done with a full-wave bridge rectifier, a buffer capacitor (330μF) and a low voltage dropout regulator which provide a stable 3.3V operating voltage. The buffer capacitor powers the electronics for six minutes after the water extraction stops, enabling the device to keep track of breaks during the shower. Showers with short interruptions (e.g., for lathering up) are treated as one coherent shower event; this means that only after an interruption of more than three minutes, the device will restart its measurement at zero and log the two water extraction events as separate shower events. Only water extraction events of at least 4.5 liters are stored; the underlying assumption is that extraction events below this threshold are due to activities like rinsing the shower tub or similar. The showers are stored in a 1024-byte EEPROM out of which 1014 bytes are reserved for shower data storage. The stock version of the device can store the final water volume and average temperature of the last 507 individual shower events. The average shower temperature is stored with a resolution of 1°C; the final water volume is stored with a resolution of 1 liter (up to 166 liters) and 2 liters (167 to 356 liters), respectively.

The main shower variables that are measured are temperature, water volume and time. Temperature values are measured with a thermistor (10 kΩ at 25°C) and sampled at a frequency of 1Hz. The energy consumption is calculated according to the heat energy $E=cp \cdot m \cdot \Delta T$, where cp = 4.18 J/(g·K) denotes the heat capacity of water, m the mass of water consumed, and ΔT the difference between the currently measured water temperature TW and the reference value (set to 6°C, a typical water supply temperature in Switzerland). This implies that the device does not account for the efficiency of the boiling unit and transportation losses, which depend on the type and age of the water heating system, pipe length, insulation etc. Based on the heat energy, an energy efficiency class rating is provided, starting at A+ at the beginning of a new shower, up to G-. Efficiency classes change at equidistant increments in energy (defined according to results of a pilot study with 60 households). Besides, a polar bear animation is displayed: based on the energy consumed, the size of the ice shell shrinks. In contrast to the other numeric-rational elements, this visualization aims to emotionally engage users and is intended to make the device more appealing to a broader audience including children.

Figure 2 shows the display of the device. It is a low power LC display with 112 segments. During the shower, the top of the display (1) changes every three seconds between the temperature and the energy efficiency class. Also in a toggling manner, the largest digits in the middle of the display (2) are used for the volume and the heat energy. At the bottom of the display (3), the polar bear and the ice shell are located. Once the extraction of water stops, the top of the display (1) stops toggling and now only shows the energy efficiency class.

Figure 2: Amphiro shower smart meter showing the current energy efficiency class [rated from A to G], temperature [°C], water volume [liters] and a polar bear animation. As soon as the water flow stops, water and energy consumption [(k)Wh] toggle.

B. *Data collection and feedback customization*

In order to access the data stored on each smart meter without damaging the waterproof housing, we developed another novel solution for optical data readout using the coil of the micro-generator and the smart meter display. The coil of the micro-generator is used to power the smart meter during the process by putting it in close proximity to an additional coil which is driven by an amplifier module. The resulting arrangement is an air-core electrical transformer that is not only used to power the smart meter, but also triggers the readout procedure. The latter is done by driving the amplifier module with a 1.6 kHz excitation signal. During the operation in the shower, the frequency of the generator signal is below 200 Hz, which ensures that a 1.6 kHz excitation signal can be recognized as the trigger to start the data readout. For the readout process, the device is placed in a box, facing a camera. As soon as the readout is triggered, the shower meter starts to display encoded data at a frequency of 6Hz, or a total shower data transfer rate of 3 bytes/s. The stored shower data is first encoded with a (7,4) Hamming code before being visualized on the display of the smart meter. The camera films the display and provides 30 frames per second at a resolution of 480 x 640 pixels. Each frame is processed on a notebook: self-written software locates the smart meter, discards duplicate frames and decodes and validates the shower data. The readout data are stored in a *.csv file along with the unique serial number of the device for a subsequent matching with the survey data. Depending on the number of showers stored, the extraction of the aggregated data can last up to five minutes per shower meter.

The device software allows for customizing both the display content and the data stored. Measurement units for temperature and water volume, for instance, can be displayed in degrees Fahrenheit and gallons. For research purposes, parts of the information typically displayed can be removed temporarily (only temperature displayed, for baseline measurements); likewise, additional feedback information can be displayed (e.g., comparisons with the previous shower). The data storage format can also be adapted to include additional values like shower duration (in seconds) and breaks (number and duration) by reducing the number of storable showers to 202. All of these customized operation modes can be triggered from the same generic software.

IV. FIELD DEPLOYMENT

A pilot test with an earlier generation of the device showed a very promising potential for such systems: the device provided normative feedback to users on the water volume used. Deployed in 60 households, the average participating household reduced their energy and water use in the shower by 22% compared to baseline use, and conservation effects were persistent for the duration of the study (one month). This successful proof of concept encouraged intensified efforts to develop the prototype into a marketable product. The device underwent numerous tests and improvements, resulting in the current version described in this paper.

Since the end of 2012, the device has been deployed in 8,000 households. A systematic two-month field study with 700 households accompanied its introduction. The goal of this user trial is to gather quantitative and qualitative insights from the field into adoption, usability, robustness, privacy concerns and user engagement. Besides, the study also investigates the size and persistence of the saving effects and the role of social context factors. The first results are promising: All except two households (99.7%) were able to install the device by themselves. None of the turbines stopped working. The pressure drop was minimal (typical 0.05 MPa) and thus accepted by nearly all participants; so were noise emissions, which are by and large drowned out by the water. Some warranty claims were made for water inside the display – the weak point has since then been identified and modified for future devices. When asked for suggestions for further development, participants mainly raised size and weight of the device as areas for improvement. 90% of the study participants indicated that they wanted to continue to use the device after the study. Two aspects should be kept in mind regarding this number: On the one hand, the sample of participants might be more proactive with regard to water and energy conservation than the general population. On the other hand, the participants had never asked for the device; they just received it by default for having completed another study. Overall, the field deployment shows that the device is fully accepted by the vast majority of users and well-suited for large-scale deployment.

V. DISCUSSION

While numerous research reports highlight in unison the potential of ICT to promote cleaner future ([36], [37], [38], [39]), the vectors to realize this potential are still fundamentally underexplored. Researchers and companies alike still need to demonstrate how the transformative power of ICT can be leveraged to create an ecologically sustainable society [3]. This is particularly true for water heating, the second largest residential energy end use. While multiple low-cost consumer-oriented products exist to monitor electric energy consumption, such innovation is clearly missing in the water domain. This is problematic from a consumption and demand management perspective alike: As consumers have very limited means to accurately monitor their water consumption, they lack effective stimuli and incentives to modify their behavior towards a more sustainable lifestyle. For demand management stakeholders, available data on water consumption do not provide a satisfying level of spatial and temporal detail, and incorrect assumptions can have important consequences, e.g., for the creation of conservation incentives or minimum water heater efficiency standards. Hence ICT can provide valuable solutions to drastically improve the management of water resources for more efficient resource and demand management strategies.

The smart water meter presented in this paper showcases a low-cost and easy-to-install sensor to measure, store and display real-time energy and water consumption data at the fixture level. Its effectiveness, robustness and practicability have been verified in a pilot study and a recent follow-up field trial with 700 households. This paper thus responds to the call for research [15] to translate behavioral science insights into successful scaled applications. The initial pilot study confirms that feedback technologies for water usage can have a considerably stronger effect than related approaches for electricity, as the perceived and factual impact of user behavior is more pre-eminent in this application. The average household in the pilot study reduced its shower energy and water consumption by 22%. A large-scale deployment of the device described in this paper in the DACH region would substantially contribute to reducing energy consumption and emissions. Assuming the same effect size of 22% and a household penetration rate of 20% (i.e. 8.2 million households in 2012), this would result in yearly savings of 1.7 TWh of energy and $5.25 \cdot 10^{12}$ liters of drinking water. The trial with 700 devices shows that low-cost and energy autarkic sensors can be deployed on a large scale and provide in-situ feedback to users that is easy to understand, concrete and actionable. The trial suggests that direct, real-time feedback has a much stronger appeal and chance to receive attention - even if conveyed on a simple display - than complex systems that require a dedicated login. The implementation of such feedback mechanisms goes beyond informative education, towards hands-on experimentation, self-incurred awareness and inclusive participation. Hence such devices can help to create a critical mass of informed and engaged citizens. That way, ICT can empower individuals and households to play a much more informed and active role in the energy transition progress and to shape a sustainable future for our society. Besides, the device serves as a successful example of energy informatics in every-day objects beyond the focus on electricity.

VI. OUTLOOK

Currently, we are still evaluating the detailed dataset of the field trial with 700 households. The goal of the analysis is to identify to what extent social and contextual factors shape the behavioral response to such an application. The aspired results are also relevant to feedback design and effective implementation of ICT feedback applications in general. Furthermore, a novel generation of devices is currently under development with wireless connectivity, based on a standard radio-frequency protocol. This will allow providing more granular and tailored feedback to users, which in turn offers an ideal research platform for testing various user engagement strategies for smart meters and feedback applications.

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[1] R. Lester and D. Hart, *Unlocking Energy Innovation: How America Can Build a Low-Cost Low-Carbon Energy System*. MIT Press, 2012.

[2] E. Williams, "Environmental effects of information and communications technologies," *Nature*, vol. 479, no. 7373, pp. 354–358, Nov. 2011.

[3] R. Watson, M.-C. Boudreau, and A. Chen, "Information Systems and Environmentally Sustainable Development: Energy Informatics and New Directions for the IS Community," *Manag. Inf. Syst. Q.*, vol. 34, no. 1, pp. 23–38, Mar. 2010.

[4] European Environment Agency, Ed., "Households and industry responsible for half of EU greenhouse gas emissions from fossil fuels." 20-Dec-2012.

[5] G. T. Gardner and P. C. Stern, "The Short List: The Most Effective Actions U.S. Households Can Take to Curb Climate Change," *Environment*, vol. 50, pp. 12–23, 2008.

[6] European Environment Agency, "Energy consumption by end use per dwelling, 2009," Mar. 2012.

[7] European Environment Agency, "Household energy consumption by end-use in the EU-27," Apr. 2012.

[8] P.-C. Fink, "Wasserversorgung: Schluss mit dem Wassersparen!," *Die Zeit*, 04-Mar-2012.

[9] VSE, "Effizienz und Elektrifizierung der Schweizer Haushalte," Apr. 2012.

[10] M. Kerstner, "Ecodesign of EuP: Lot 2 - Water heaters," Brussels, Jul-2008.

[11] C.-L. Cheng, "Study of the inter-relationship between water use and energy conservation for a building," *Energy Build.*, vol. 34, no. 3, pp. 261–266, Mar. 2002.

[12] D. J. M. Flower and V. G. Mitchell, *An Integrated Approach to Modelling Urban Water Systems*. Monash University, 2009.

[13] A. Arpke and N. Hutzler, "Domestic Water Use in the United States: A Life-Cycle Approach," *J. Ind. Ecol.*, vol. 10, no. 1/2, 2006.

[14] U.S. Department of Energy, "Buildings Energy Data Book," Apr. 2012.

[15] H. Allcott and S. Mullainathan, "Behavior and Energy Policy," *Science*, vol. 327, no. 5970, pp. 1204–1205, Mar. 2010.

[16] J. Graham, "Conserving Energy by Inducing People to Drive Less," *J. Appl. Soc. Psychol.*, vol. 41, no. 1, pp. 106–118.

[17] M. Baeriswyl, W. Przepiorka, and T. Staake, "Identifying individuals' preferences using games: A field experiment in promoting sustainable energy consumption," *Icis 2011 Proc.*, Dec. 2011.

[18] M. Baeriswyl, T. Staake, and C.-M. Loock, "The effects of user identity and sanctions in online communities on real-world behavior," *Icis 2011 Proc.*, Dec. 2011.

[19] C.-M. Loock, T. Staake, and J. Landwehr, "Green IS Design and Energy Conservation: An Empirical Investigation of Social Normative Feedback," *Icis 2011 Proc.*, Dec. 2011.

[20] A. Faruqui, S. Sergici, and A. Sharif, "The impact of informational feedback on energy consumption—A survey of the experimental evidence," *Energy*, vol. 35, no. 4, pp. 1598–1608, Apr. 2010.

[21] K. Ehrhardt-Martinez, K. A. Donnelly, and J. A. "Skip" Laitner, "Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities," ACEEE Research Report E105, 2010.

[22] S. Houde, A. Todd, A. Sudarshan, J. A. Flora, and K. C. Armel, "Real-time Feedback and Electricity Consumption: A Field Experiment Assessing the Potential for Savings and Persistence," *Energy J.*, vol. Volume 34, no. Number 1, 2013.

[23] S. Darby, "The effectiveness of feedback on energy consumption. A review for DEFRA of the literature on metering, billing and direct displays," 2006.

[24] C. Fischer, "Feedback on household electricity consumption: a tool for saving energy?," *Energy Effic.*, vol. 1, no. 1, pp. 79–104, Feb. 2008.

[25] P. C. Stern, "Contributions of Psychology to Limiting Climate Change," *Am. Psychol.*, vol. 66, no. 4, pp. 303–314, 2011.

[26] J. Froehlich, L. Findlater, M. Ostergren, S. Ramanathan, J. Peterson, I. Wragg, E. Larson, F. Fu, M. Bai, S. Patel, and J. A. Landay, "The design and evaluation of prototype eco-feedback displays for fixture-level water usage data," *SIGCHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2012, pp. 2367–2376.

[27] R. P. Evans, J. D. Blotter, and A. G. Stephens, "Flow Rate Measurements Using Flow-Induced Pipe Vibration," *J. Fluids Eng.*, vol. 126, no. 2, pp. 280–285, May 2004.

[28] Y. Kim, T. Schmid, Z. M. Charbiwala, J. Friedman, and M. B. Srivastava, "NAWMS: nonintrusive autonomous water monitoring system," in *Proceedings of the 6th ACM conference on Embedded network sensor systems*, New York, NY, USA, 2008, pp. 309–322.

[29] E. Larson, J. Froehlich, T. Campbell, C. Haggerty, L. Atlas, J. Fogarty, and S. N. Patel, "Disaggregated water sensing from a single, pressure-based sensor: An extended analysis of HydroSense using staged experiments," *Perv. Mob. Comput.* 8(1), pp.82–102, Feb. 2012.

[30] E. Arroyo, L. Bonanni, and T. Selker, "Waterbot: exploring feedback and persuasive techniques at the sink," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2005, pp. 631–639.

[31] S. Kuznetsov and E. Paulos, "UpStream: motivating water conservation with low-cost water flow sensing and persuasive displays," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, 2010, pp. 1851–1860.

[32] K. Kappel and T. Grechenig, "'show-me': water consumption at a glance to promote water conservation in the shower," in *Proceedings of the 4th International Conference on Persuasive Technology*, New York, NY, USA, 2009, pp. 26:1–26:6.

[33] M. Laschke, M. Hassenzahl, S. Diefenbach, and M. Tippkämper, "With a little help from a friend: a shower calendar to save water," in *CHI'11 Extended Abstracts on Human Factors in Computing Systems*, Vancouver, BC, Canada, 2011, pp. 633–646.

[34] R. M. Willis, R. A. Stewart, K. Panuwatwanich, S. Jones, and A. Kyriakides, "Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households," *Resour. Conserv. Recycl.* 54(12), pp. 1117–1127, Oct. 2010.

[35] V. Tasic, T. Staake, T. Stiefmeier, V. Tiefenbeck, E. Fleisch, and G. Troster, "Self-powered water meter for direct feedback," *Internet Things Iot 2012 3rd Int. Conf.*, pp. 24–30, 24.

[36] G. Boccaletti, M. Löffler, and J. M. Oppenheim, "How IT can cut carbon emissions," *McKinsey Quarterly*, Sep-2008.

[37] Economist Intelligence Unit, "Managing the company's carbon footprint - The emerging role of ICT."

[38] Cisco, "The Sustainable Business Practice Study," 2008.

[39] J. M. D. Barroso, "Europe's Climate Change Opportunity," Brussels, 23-Jan-2008.