Smart Energy: Electricity Usage and Demand-Side Management in Households

Ubiquitous Computing Seminar FS2014

Student report

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ABSTRACT

Household electrical energy consumption represents a major chunk of the total demand. This demand is also exhibiting steady increase whereas supplies are struggling to keep up. This poses two key challenges to Demand-Side Management (DSM) – achieving unrealized energy savings and, reducing peak loads. Energy saving in households has not yet achieved its potential chiefly because of poor feedback mechanism leading to insufficient consumer participation. Strategies to control demand (and hence peak load) are also becoming important in view of increasing diversity of appliance usage and appearance of renewable energy sources. In this report, we shall argue that application of Information and Communication Technology (ICT) to energy management is the cornerstone of turning SmartGrids to result in Smart Energy infrastructure.

Keywords: Smart Energy, Demand-Side Management, Demand-Response in residential usage, Smart Meters.

INTRODUCTION

Statistical data from various countries [5, 10, 13] reveal that households contribute up to 40% of the electrical energy demand. As compared to commercial or industrial usage, electrical energy demand in households varies. This is largely due to environmental, economic, behavioral and geographic factors. In developed and industrial nations, households use a large part of electrical energy for the purpose of heating or cooling, followed by process devices (like washing, drying, refrigeration etc.). But there is also a significant contribution from lighting, appliances for entertainment electronics and computing. Figure 1 shows the electrical energy consumption on average in households in Switzerland. Apart from the major consumers (like heaters and air conditioners) there is also a growing use of smaller appliances which are often ignored when it comes to optimization of usage. This happens because they are mostly “invisible” to the user who wishes to implement energy saving measures. For example, a Multimedia PC in the living room which runs continuously consuming about 50W of power effectively causes about 1 kWh of energy consumption per day. In this case had the user been informed about the consumption of the particular appliance along with suggestions (like the possibility to set the device to standby mode), then there is a larger chance of the user taking action based on the suggestion. Similarly, if the energy supplier could know about the usage pattern in the households then they could fine-tune their Demand-Response strategies with targeted pricing incentives to control the peak load occurring in the grid.

The key to achieving energy savings and controlling peak load appears to hinge around energy monitoring and data exchange infrastructure. Improved monitoring can result in more meaningful feedback to the user and simultaneously provide the supplier rich data to model the demand (and consequently the DR strategies). Consumption data forms the backbone of Smart Energy systems, but its acquisition in an economically feasible manner is still a challenge. However, the gathering, processing, interpretation, and exchange of data can be enabled in a cost-effective manner by a well-designed information and communication technology (ICT).

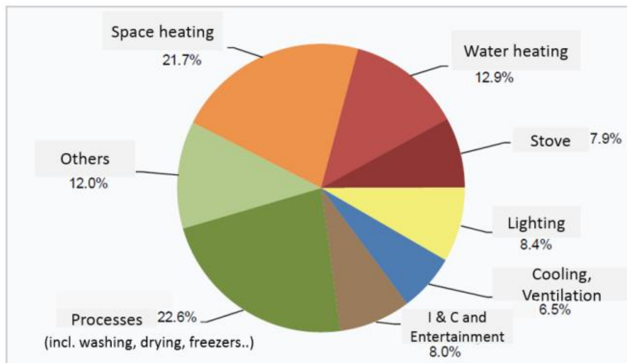

Figure 1: Usage of electrical energy in residential sector (in Switzerland). Adapted from [10].

In this report, we first look at two key problems –peak load in the grid and, sub-optimal energy savings in households. We then go on to highlight specifically the possible role of Smart Energy in alleviating these problems. In specific, we discuss how Smart Meters can serve to provide combined energy monitoring and data exchange infrastructure, thus resulting in reduction in peak load and energy consumption on the whole in residential usage. In the following discussions, we will also examine the shortcomings and challenges facing implementation of Smart Energy systems for households.

THE PROBLEM OF PEAK LOAD

As viewed by the energy supplier, demand appears to be a result of stochastic processes whereby usage variances at each consumer aggregate to produce a so-called “load curve”. The load curve however shows some generally noticeable patterns – there are periods when the demand rises to a peak. The time of occurrence and the magnitude of the peak varies between electricity supply grids. Figure 2 shows the load curve in the Swiss Grid depicted over the day and months of a year [10]. In order to cater for the peak load, the electricity grid has to be sized accordingly and hence incurs higher investment. Apart from the economics

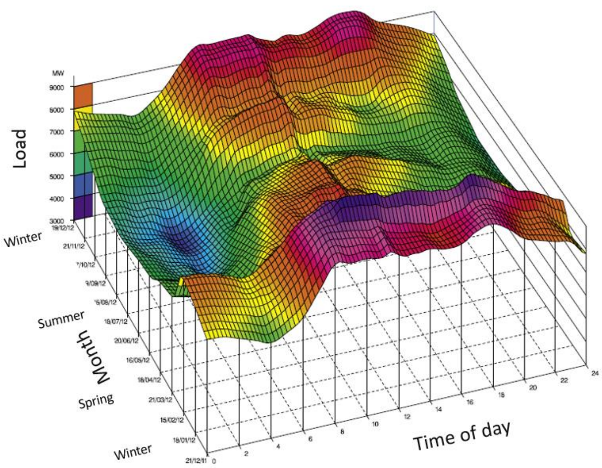

Figure 2: Electricity demand (in MW) experienced by the grid in Switzerland through the day in various months of the year. Adapted from [10]

of constructing the grid, peak load also results in inefficient generation of energy. These two aspects are briefly described below.

Peak load and grid sizing

Generators, distribution networks, switching substation and transformers need to be designed for the expected maximum power demand. This results in a system that is almost 50% larger than what would be needed if the demand was nearly flat (at the average value). Hence, a large part of the generation and distribution capacity remains unutilized. Had the demand been an almost flat curve, it would have resulted in lower investment requirements to build up the grid.

Peak load and generation efficiency

Electrical generators cannot be started in short notice periods as they need substantial time to be primed and stabilized. In order to cater for the peak load periods, the energy supplier keeps the generators running constantly at mostly part load capacity. This is termed as “spinning reserve”. When a generator is run at part load, its electrical efficiency is much lower than full load – this results in inefficient utilization of the energy source.

TACKLING PEAK LOAD USING DEMAND-SIDE MANAGEMENT

Peak load has been a long known problem amongst energy suppliers and a spectrum of strategies has been evolved to counter it. The collection of such strategies, tools, and technologies to manage demand is a part of the wide topic of DSM. In this context, there are principally two parallel approaches – the first is to try and reduce consumption by promoting energy efficient technologies, and the second aspect deals with controlling the demand. The latter approach, termed as Demand-Response (DR), provides an effective instrument to control demand by means of intervention, incentives or reserve management. Figure 3 presents DSM methods in summary. Though DR’s intent is to flatten the demand curve, it can result in so called “rebound” [1, 2, 5] which causes the peak to shift rather than flatten (refer Figure 4). The primary cause of rebounds is application of DR without adequate knowledge of demand characteristics and without technology support to the consumer to participate in a DR event.

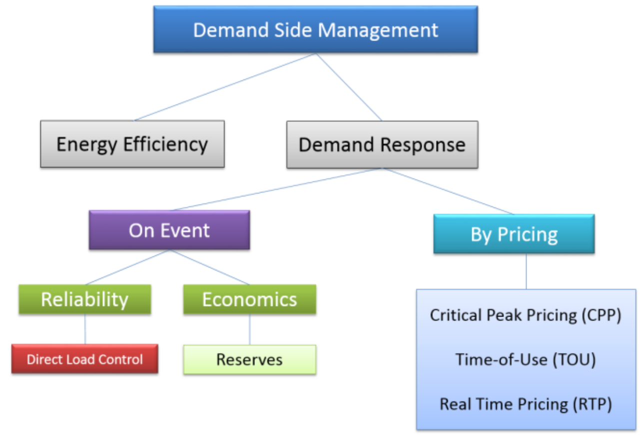

Figure 3: Overview of strategies focused on peak load reduction.

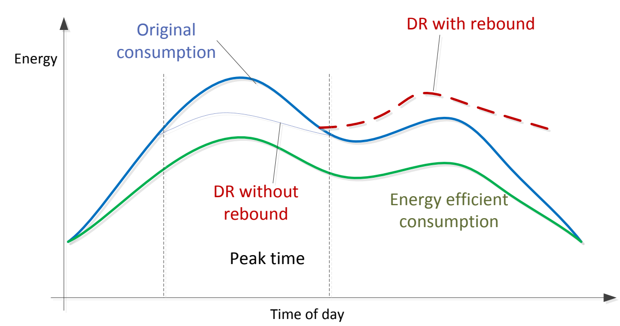

Figure 4: Load curves showing energy demand and the effect of DSM strategies.

Shortcomings of DR in households

Hitherto, energy suppliers have focused their attention on non-residential sectors to implement intelligent DR strategies. This is primarily due to the large investment required to establish ICT infrastructure to support interactive DR. Also, the load diversity in non-residential sectors is relatively easy to model. As a consequence, energy suppliers know much less about residential energy consumption patterns and have limited capability to cause direct load control. Pricing incentives, which are mostly based on Critical

Peak Pricing (CPP) or on simplified Time Of Use (TOU) have had limited effect due to low perceived savings and lack of widespread automated controls to support pricing signal based appliance operation. Implementation of automated load control based on dynamic pricing is limited to select few appliances like water heaters and air-conditioners. The reason for this limited technology support for direct load control in households is primarily cost. Even today, the rather old technology of Ripple Control[1] is largely being used. On the other hand, the ICT infrastructure at home and the ability of appliances to participate in an intelligent network are very limited. In order to overcome this technology lag, there is an emerging move towards defining "Home Area Network" or HAN which will serve to integrate appliances, feedback devices together with data from the energy supplier. Once again, though there is visible progress in attempts to define and standardize HAN, the challenges are multifold in view of the diversity of usage, manufacturers and available technologies. Finally, there have not been many studies on the behavioral aspects of household consumers and in particular the reason for lack of motivation in participating in Demand-Side Management [5].

ENERGY SAVINGS IN HOUSEHOLDS

We now move our focus to the second problem of DSM in households – namely, how do we achieve the unrealized energy savings? Several studies (see references in [5]) have pointed out that the energy savings potential is household is much larger than what is being achieved now. Almost unanimously, the studies agree that the key to realizing this potential lies in improved user feedback. Figure 5 shows that more than 12% savings can be achieved by including appliance level feedback along with suggestion.

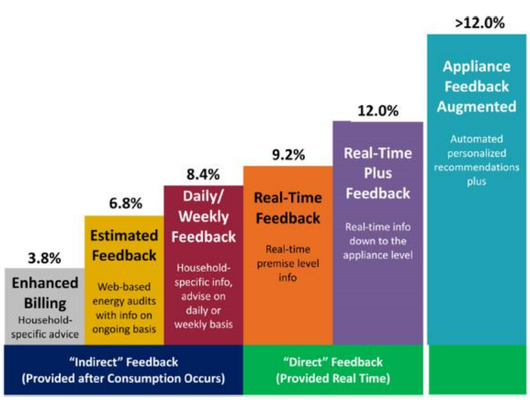

Figure 5: Effect of improved feedback on energy saving in household electricity consumption (from [5])

Amongst the many common-sense recommendations for improving feedback to the consumer, the following factors have been found to be especially effective:

1. Providing feedback as soon as possible after consumption.
2. Customizing the feedback to the household's circumstance.
3. Comparing the consumption to a meaningful benchmark.
4. Providing appliance level consumption data along with recommendations for improvement.

The above factors are invariably tied to the capability of obtaining consumption data from households and appliances in a household.

Figure 6: Some examples of easily accessible energy feedback for the home user. From [9].

This calls for a thoughtful implementation of technologies under the aegis of Smart Energy. We now illustrate how such technology implementations can bring tangible benefit by examining the possibility access to appliance level consumption data.

How to obtain appliance level data?

Appliance level data can be obtained principally by either of two approaches – intrusive or non-intrusive measurement. Intrusive measurement incurs metering device being installed at the electrical outlet where the appliance is connected. There are two key disadvantages inherent in this approach – high cost of installation and difficultly in integrating the data to DR mechanisms. In order to overcome these difficulties, non-intrusive appliance load monitoring gained momentum and several researches have shown promising yields.

Non-intrusive load monitoring

In this approach load consumption is measured at a central metering unit and a computational algorithm is employed to reconstruct operation periods of appliances. The algorithm, termed as *disaggregation*, attempts to detect state changes by observing the load curve and compares the magnitude change in load to a pre-stored library of appliances. Figure 7 shows the total load curve and the state transitions recognized by change in magnitude of power[2].

The performance of a disaggregation algorithm is usually stated in its ability to distinguish appliances and correctly

[1] Ripple Control involves one-way signaling of low tariff period by injecting an audio-frequency harmonics into the supply line. The data content is limited to few bytes.

[2] Note that this is rather simplified figure to explain the concept. Total power in itself is rather insufficient to distinguish appliances and often multiple measurement parameters (such as reactive power and transient harmonics) are considered.

predicting the load consumed by each appliance. In order to achieve high quality in its performance the algorithm needs to be fed with measurement data at a sampling interval as small as possible (in the order of 100 kHz). Also, combinations of measured load parameters are considered (at least total and reactive power). Higher frequency sampling enables discovery of appliances which can be distinguished only by its transient consumption patterns whereas including multiple measurement factors enables division of the clustering space.

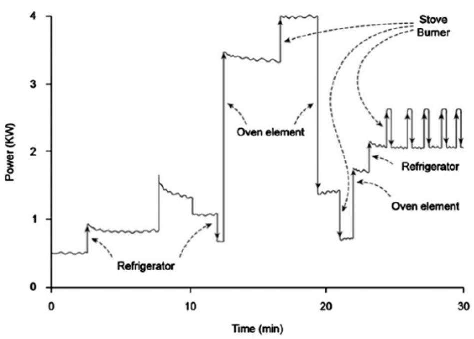

Figure 7: Disaggregation algorithms attempt to detect state changes in the load curve and compare the magnitudes against a pre-stored library of appliances. From [8].

To achieve this rather computation intensive operation, the algorithm needs to have high speed communication interface to the meter. In view of this, it is preferable to host the disaggregation computation on the metering hardware itself. Metering technology has evolved considerably from the old electro-mechanical meters, followed by electronic hardware with communication capability, to the current SmartMeter technology. SmartMeters provide metrology, computation and communication platform combined into one unit. The communication capability of the SmartMeter extends in two directions – towards the energy supplier via the wide area network (WAN), and towards the consumer via the HAN. Hence the SmartMeter has the potential to act as a key information gathering, processing and exchange gateway in the implementation of Smart Energy for households.

Other than enabling more meaningful feedback to the consumer, appliance level data, when shared, also provide an opportunity for the appliance manufacturer to improve their design. For example, a manufacturer of washing machines can analyze the wash and spin cycles to determine the commonly used operation sequence and focus their attention on optimizing it. In addition, appliance level data, in particular of larger appliances, would be of interest to the energy supplier to understand the causes of demand and hence improve their model.

TOWARDS SMART ENERGY

In the preceding discussions we have seen how energy consumption data of households can serve to help energy suppliers build an accurate demand model and also how such data, especially appliance level data, helps in providing a more meaningful feedback to the user. There is in fact, a subtle relationship between peak load reduction and achieving energy savings – they tend to go hand-in-hand in the sense that it prompts the consumer to review energy consumption in general and bring about more efficient usage. In the current situation regarding energy policies, there is a strong movement towards unifying generation and distribution networks by employing the tools and technologies of SmartGrid. On the metering front, we have the SmartMeter, which provides an opportunity for data processing and exchange. Demand-Side Management needs to seamless integrate energy monitoring with energy management and this is the crux of Smart Energy.

ICT infrastructure for Smart Energy

DSM for households needs bi-directional information exchange. From the energy supplier, information related to dynamic pricing and direct load control needs to be sent in a targeted manner (to households and specific appliances therein). Also, the consumer needs to be informed about consumption and billing data. In the other direction, the information regarding usage and feedback regarding willingness to participate in DR incentives needs to flow back to the energy supplier. To enable this, a communication infrastructure binding the parties needs to be in place. Figure 8 visualizes such a communication infrastructure in an abstract manner.

Figure 8: Communication network for Smart Energy infrastructure.

Communication between the energy supplier and the Smart Meter hardware (WAN) already exists to a large degree[3]. The topology and intent of this communication is rather one-to-many with the energy supplier reading meter data for billing and sending energy tariff for dynamic pricing. The physical channel used is mostly Power Line Communication (PLC) or GSM/GPRS based network. The amount of data exchanged on this network is limited due to bandwidth restriction of the physical channel. Some infrastructure implementations do not use the WAN, but instead the communication is channeled using the internet – this is

[3] Mostly used for Automated Meter Reading (AMR).

however subject to availability of reliable internet access and security risks carried in using it.

Communication infrastructure for HAN has yet to reach a consensus amongst manufacturers. Some of the technologies currently in use are Ethernet LAN, WiFi, HomePlug, Z-wave, openHan and ZigBee [17]. The HAN needs to incorporate devices like the Smart Meter, Smart Thermostat, in-home display (for energy feedback), Plug-in electric vehicles, Smart Appliances and energy management system for renewable energy sources like solar or wind power. These devices are physically distributed throughout the household and hence any network technology adopted should be capable of providing low-cost and reliable networking. The bandwidth requirement is rather modest – the data exchanges are mostly in small packets and event oriented.

Apart from the physical infrastructure for communication in the HAN and the WAN, an equally important factor is the design of application protocol on these networks. So far, only two specifications, the openADR [16] and the ZigBee Smart Energy Profile [17] have attempted to lay structure to the inter-communication between energy supplier, SmartMeter and intelligent devices in the home (like the SmartThermostats). The interactions are however limited to either DR event communication (openADR) or to integration of metering data (ZigBee SEP). On a broader scale, what is required is an application protocol and framework to establish interaction between the devices (M2M) and between the Smart Energy management system and the consumer. M2M interactions are diverse and difficult to model. For example, interactions like the planning of charging cycle for an electric vehicle depending upon the DR requests received at the Smart Meter or the availability of energy from Solar panels needs case-to-case analysis. Hence the nature and content of communication is difficult to standardize. Similarly, the interaction between the consumer and the system on the whole also has diverse requirements. For example, to incorporate the calendar schedule of the consumer within the planning algorithm of the Smart Thermostat requires clear definition of data structures to be constructed (by the human input device) and consumed (in this case, by the Smart Thermostat). Hence, ICT infrastructure for Smart Energy implementation in household is currently in a disarray of standards and uncovered requirements and presents a very rich area for research

SMARTMETER AS A KEY COMPONENT

As mentioned above, despite the availability of an energy measurement platform along with communication and computation infrastructure in the shape of SmartMeter, benefits have not been realized. In addition, the lack of consensus, standardization and inter-operability in the HAN has led to stagnation in progress towards effective DSM for households. As a first step, we believe that the role of SmartMeter should be carefully reviewed and long term technology strategies should be built on it. This view is also expressed in [5] where the authors advocate holding off investments in SmartMeter deployments until its utilization is defined in a more optimal manner.

Figure 9 summarizes the role which a SmartMeter can play in achieving effective DSM. On the whole, there are two sides to the utilization of the SmartMeter – the supplier and consumer parts. We now briefly describe how DSM strategies can be supported by the SmartMeter in its role as information gateway.

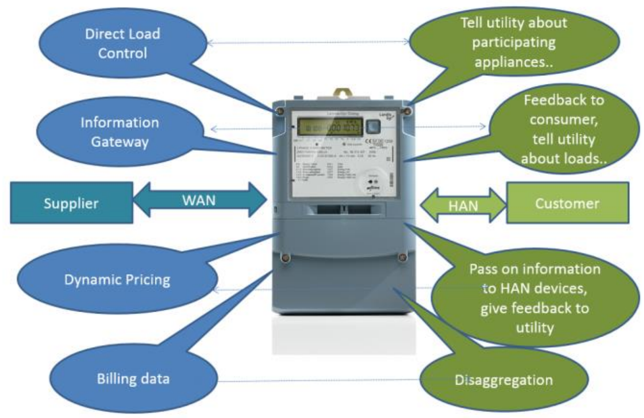

Figure 9: Using SmartMeter as information gateway between the supplier and the consumer.

Direct load control

The energy supplier can transmit DR events in a granular manner based on the past usage history of the household. For example, instead of the DR event being merely "curtail load", it can be elaborated as "curtail use of dryer, and prevent air-conditioning setpoint lower than 24 °C". This signal is based on the knowledge that there is a high probability of the consumer using the appliances. On the other hand, the consumer can input DR participation preferences by stating usages that can be postponed or reduced. Continuing on the example, the consumer can state "need to user dryer today between 13:00 and 14:00". Such interactive DR has a higher potential for success. This however brings complexity of modeling the data and interaction and it is hoped that combination of generally known abstract models and country or circumstance specific extensions would alleviate the complexities.

Information gateway

Assuming that non-intrusive load monitoring enables the SmartMeter to have detailed knowledge about appliances and their usage, the information can be passed on to the supplier who can then use it to build a model of demand. The supplier can then provide feedback regarding consumption behavior along with suggestions for improvement. For example, the supplier can observe that the energy consumed by the electric boiler has been consistently increasing and consequently warns the consumer along with a suggestion to perhaps have it de-calcified. The supplier can also give comparative feedbacks regarding the consumption. For example, the consumer can be told that their energy requirement for washing and drying is below the average consumption for household of similar circumstance (given the assumption that the supplier knows about the circumstances like number of people living, the kind of building construction etc.).

Dynamic Pricing

The energy supplier can employ more flexible pricing schemes which are fine tuned to the household and offer it to the consumer. This proposal is then visible to the consumer via in-home displays or personal information systems and the consumer then can choose to participate in the offer. For example, the supplier offers a tariff rebate if the consumer agrees to increase the air-condition setpoint to 25 °C. In this case, the rebate offer appears on the SmartThermostat which the user can choose to accept or reject. The decision is sent back to the supplier who has now a more deterministic employment of dynamic pricing (in comparison with traditional methods where the supplier has no feedback about potential participation).

Augmented Billing

The overall data about usage, appliances, DR events and dynamic pricing can now be used to provide informative billing content. For example, the supplier can state in the energy bill that by participating in the dynamic price offer the consumer saved a certain amount of money. Based on past history of consumption, the supplier can state the expected energy consumption for the coming months and suggest participation in tariff incentives.

PRIVACY ISSUES

As with most technologies and aids which collect some form of data from which human activity can be deduced, there is concern about data privacy when it comes to Smart Metering. Summarily there are two aspects of concern – access to appliance usage data, and ability to directly control load in the household. In the first case, if data is not securely transmitted and stored, it can lead to infringement on the personal sphere of the user. For example, one could deduce from the consumption data if the user is at home or not, or find out if the user has a certain appliance (which can then be misused for unsolicited marketing). In the second case, consumers fear that their use of electrical appliances, and hence their daily activities, would be regulated by the energy supplier. Though there has been no documented case of breach of privacy resulting from data obtained in a Smart Energy system, the concerns are valid. But the solution to this is bound to the topic of network and data security in domains of “Internet of Things” and Cloud computing. However, a solution that is generic to all usages in the above mentioned domains might be difficult to find and hence one other important dimension of Smart Energy will be data and network security.

WHY SMART ENERGY IS NOT YET A SUCCESS?

Some studies paint a rather bleak picture of Smart Meter implementation in households [5][13] whereas others [12] show remarkable success in achieving reduction of peak loads and energy consumption. In general, the deployment of SmarMeters which resulted in the energy suppliers merely using it for billing data read-out have resulted in no benefit in achieving energy savings or peak load reduction. This is not surprising considering our above discussions where we highlighted the need for user participation (driven by effective feedback). However, in cases where the energy suppliers did use the data to provide feedback, the benefits were only marginal. Here, the cause seemed lie in the insufficient quality of the feedback (for example, provided after a long time gap). On the other hand, deployments such as the one in Ireland [12] demonstrated strong user participation in response to granular and specific feedback regarding their consumption. Similarly, DR strategies without the support of technology showed a significantly low effect as compared to scenarios where DR was supported by automation (like pricing signals directly reaching the SmartThermostat instead of requiring user intervention to program the thermostat). Apart from technological issues, behavioral aspects have not yet been explored and studied [5, 15, 18]. This has resulted in inconsistent results when deployments were extended beyond a study sample.

CONCLUSION

We have examined the problems of DSM in households and realized that the solution lies in effective implementation of Smart Energy. Such a solution would cover ICT infrastructure, application modeling and behavioral understanding. One of the core achievements of such a system for households would be to obtain granular consumption data and utilize it for meaningful feedback and DR. Without a carefully designed system there is a risk that the investment in the infrastructure will not fetch any benefit. The deployment of DSM in household also poses the challenge due to the size involved (number of households) and need for low-cost solution. In view of this, research in Smart Energy is perhaps one of the most fruitful objectives to pursue under the topic of Pervasive Computing.

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