Exploiting Demand Response in Web-based Energy-aware Smart Homes

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***Abstract*—Energy conservation is a global issue with tremendous environmental implications. By 2030, the global energy demand will double. High demands and environmental concerns, force the transformation of electricity grids into smart grids, towards more rational utilization of energy. Residential smart metering transforms homes into energy-aware environments, allowing residents to make informed choices about electricity. Web-based smart homes employ Web principles to interconnect electrical appliances. The Web, as a highly ubiquitous platform, can be used to connect energy-aware smart homes to the smart grid. An important characteristic of the future grid is demand response, defined as real-time pricing, according to supply conditions. Energy-aware smart homes can exploit this capability to schedule electricity-related tasks for future execution. We investigate this possibility by deploying a Web-based, energy-aware smart home, adapted to demand response. An initial technical study denotes the feasibility of our approach and a small survey indicates the potential for saving energy and money.**

***Keywords*-Smart Home; Smart Meters; Electrical Appliances; Smart Grid; Demand Response; Web.**

I. INTRODUCTION

Energy conservation is a big issue in the world with tremendous environmental, political and social implications. Predictions denote that by the year 2030, the global energy demand will double, rising up the energy-related green gas emissions by 55% [1].

This high energy demand cannot be accommodated by current electricity grids. Most of the electricity grids around the world have been designed many decades ago, to meet the energy requirements of the society at that time.

Increasing demand and environmental concerns, influenced initiatives towards more rational utilization of electrical energy. This goal can be achieved when the electric utilities are fully aware in real-time about the electrical consumption and the demands of their customers. The grid becomes intelligent when it manages to deliver electricity from suppliers to consumers using two-way digital communications and a smart metering system. This vision is believed to convert traditional electricity grids into modern *smart grids*.

Smart metering of electricity does not only affect the future development of the smart grid, but also motivates the rational management of the electrical consumption in houses and buildings. Buildings consume a large proportion of the total electrical energy [2]. This fact has a significant environmental impact, as more than 30% of all greenhouse gas emissions can be attributed to buildings.

Residential smart meters are devices that measure in real-time the energy consumption of a house, or even of various electrical devices and control their operation. These meters have gained popularity recently. For example, it is planned that every home in Britain will be equipped with such meters by 2020. Equipping home area networks (HAN) with smart meters, allows the enablement of *energy-aware smart homes*.

According to numerous studies such as [3], timely electrical consumption feedback through smart metering, is believed to reduce electrical consumption by a fraction of 5-15%.

However, further savings can be achieved, when energy-aware smart homes get connected to the smart grid. The Web is an appropriate platform for such a wide-scale interconnection.

In this work, we assume the existence of the smart grid and we develop an energy-aware smart home that can exploit the demand response functionality offered by the grid, through the Web. In such a way, home residents can save money, while electric utilities can save energy and be assured about the societal acceptance of the grid and its smooth operation.

The rest of the paper is organized as follows: Section II provides background information as well as related work, while Section III argues about the benefits of using the Web as an integration platform. Then, Section IV presents the system's implementation and Section V discusses the technical feasibility of our approach. Finally, Section VI investigates possible savings through a small case study and Section VII concludes the paper.

II. RELATED WORK

Our approach spans in two research domains: HAN equipped with residential smart meters and the smart grid.

In the following subsections, we present some background information regarding the smart grid and energy-aware home environments, along with significant related work in the fields.

A. Towards the Smart Grid

The smart grid is expected to provide advanced functionalities such as high power quality, immediate failure alarms,

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reliability, security and improved customer service.

An important characteristic of the smart grid is real-time pricing, which is a smart energy pricing scheme that is set for a specific time period on an advance basis and which may change according to load demands or price changes in the market. Prices paid for electricity consumed during these periods are known to consumers a priori, letting them to vary their energy usage in response to these prices and manage their energy costs by shifting usage to a lower tariff period. This mechanism is mainly known as demand response (DR).

Many experts state that Plug-in Hybrid Electric Vehicles (PHEV) will be the grid's killer application. PHEV are hybrid vehicles with rechargeable batteries that can be restored to full charge when connected to an (external) electric power source.

For example, a study from the Pacific Northwest National Laboratory [4] states that even the existing grid in the United States, if optimally utilized, could provide enough power for PHEV to replace up to 73% of the nation's cars. However, if the charging times of PHEV are not properly managed, the load to the grid's distribution network will be highly increased. The smart grid can afford this issue by means of DR. Improved tariffs, adjusted to reflect the system's congestions, would promote proper scheduling of plug-in vehicle charging.

Pilot projects that implement the smart grid in an experimental basis have appeared lately. A popular pilot project is SmartGridCity [5], performed by Xcel Energy utility supplier in the area of Boulder, Colorado.

Masdar City [6] will be the world's first zero-carbon city, powered entirely by renewable energy sources. Pilot residences will be equipped with DR-enabled smart appliances. By receiving signals from the grid, they will customize the appliances' usage to reduce energy demand on the grid.

The interconnection of smart homes and the smart grid through the Internet, by means of Web services is proposed in [7]. It is stated that service-oriented architectures are well suited for the smart grid.

B. Energy-aware Smart Homes

Residential smart metering transforms home environments into energy-aware smart spaces. There exist two broad categories for household energy monitoring and control: whole-home and device-specific.

Whole-home approaches place one smart meter where the home connects to the power grid. Marchiori et al. [8] use circuit-level power measurements to separate aggregated data into device-level estimates, with 90% accuracy. ViridiScope [9] places inexpensive sensors near electrical appliances to estimate their power consumption with less than 10% error.

Traditional smart meters offer a house-level granularity, where only the whole-home energy consumption can be visualized. As the technology becomes more advanced, monitoring the energy consumption of each electrical appliance and controlling its operation, becomes possible. Device-specific techniques plug smart meters in individual electrical appliances.

Some device-specific smart meters offer even wireless networking capabilities, extending the residential smart metering infrastructure into a robust wireless network. As an example, Ploggs [10] incorporate wireless transceivers, based on the IEEE802.15.4 wireless standard.

ACme [11] is a high-fidelity AC metering network that uses wireless sensors, equipped with digital energy meters to provide accurate energy measurements of single devices. Energie Visible [12] employs smart meters to visualize in real-time the energy consumption of the appliances that are connected to the meters, in a Web interface. In the Energy Aware Smart Home [13], users can use their mobile phones as magic lenses to view the energy consumption of their appliances, by pointing out them with the phone's camera.

A big challenge for energy-aware smart homes, taking into account the existence of the smart grid, is to provide to the home environment visibility of grid conditions and dynamic prices, in order to take local decisions and intelligently control the usage of household electrical appliances, to save energy and money. Studies that specifically examine the implications of demand response functionality of the smart grid in energy-aware smart homes are still lacking, to our knowledge.

III. THE WEB AS AN INTEGRATION PLATFORM

We believe the Web is an appropriate platform for bridging energy-aware smart homes and the smart grid. By means of the Web, smart homes can be fully synchronized with the grid.

The Web is highly ubiquitous and it scales particularly well. Almost every house has Internet connectivity today, while technological advancements in mobile telecommunications such as 3G and WiMAX, permit the Internet to penetrate in the mobile world.

A. The Web and the Smart Grid

We identify many benefits in using the Web as an integration platform for the smart grid.

A cloud-based smart grid strategy constitutes a cost-efficient practice for enhancing grid's functionality incrementally as energy demands arise. New capabilities can be implemented in parallel with existing operations and systems, while the impact on ongoing operations is minimized.

Existing systems can be securely integrated with new components and further be connected to users and customers, by means of the Web. The Web is a scalable framework for incorporating third-party and partner techniques.

Most importantly, utilization of the Web would promote the Web service model, minimizing expenses for additional infrastructure and overall implementation time. Web services are core parts of cloud computing, providing a wealth of proven methods for systems integration.

B. Web-based Smart Homes

Designing smart homes based on the Web principles is a recent practice. In the Web Home application framework [14], we reused central principles of the modern Web architecture to integrate physical devices to the Web and build an interoperable smart home that supports multiple home residents concurrently. By using the Web as application layer, flexible applications on top of heterogeneous embedded devices can be built with a few lines of code, facilitating home automation.

Web-based smart homes build upon the notion of the *Web of Things* [15], which is about employing well-accepted Web practices to interconnect the quickly expanding ecosystem of embedded devices, built into future household appliances.

REpresentational State Transfer (REST) [16] is proposed for Web-based interaction with household appliances as it is a lightweight architectural style that defines how to use HTTP as an application protocol. REST advocates in providing Web services modeled as *resources*. Resources can be manipulated by the methods specified in the HTTP standard, under a uniform interface. REST guarantees interoperability and a smooth transition from the Web to home environments.

Enabling home appliances to the Web, permits the extension of Web mashups into *physical mashups* [17]. Physical mashups take advantage of real-world services offered by physical devices and combine them using the same tools and techniques of classic Web mashups. In this way, physical devices can be blended with Web content and services, without much effort.

A future cloud-based smart grid strategy would allow the seamless integration of the grid with Web-based, energy-aware smart homes. As an example, what follows is a shell script that implements a physical mashup, combining electrical appliances and Web services provided by an electric utility.

We assume in this example that the utility exposes, as a RESTful Web service, information about its real-time tariffs. This script checks the current home tariff and starts charging automatically a hybrid electric vehicle as soon as the tariff falls below some defined limit.

```
function check {
   if [ $? -le LOW_TARIFF ] ; then
       curl -d "State=ON"
            -X PUT [HomeAddress]/PHEV/Switch/
   fi
}
curl -s -X GET [UtilityAddress]/Tariff/Home/ $1
check;
```

Through the Web, residents can pull easily the data they need from an open API offered by their electric utility, and use them right away in their own applications, in any programming language that supports HTTP.

As a more general example, a reliable Web-based weather forecast service can be combined with smart appliances, e.g., to turn off the electric heating automatically, in case the temperature is about to increase in the next few hours.

These simple examples indicate that advanced home automation, high flexibility and energy conservation can be achieved, when using the Web as a platform.

IV. Developing a Web-based Energy-aware Smart Home

We extended our Web Home framework [14] to support interaction with residential smart meters and consequently with the electrical appliances of a smart home.

We utilized Plogg residential meters to create a wireless smart metering network inside the house. We exploit the fact that wireless sensor networks can provide a reliable and extensible solution for real-world deployments. Each Plogg is associated with some specific appliance, in order to monitor its electricity footprint and control its operation.

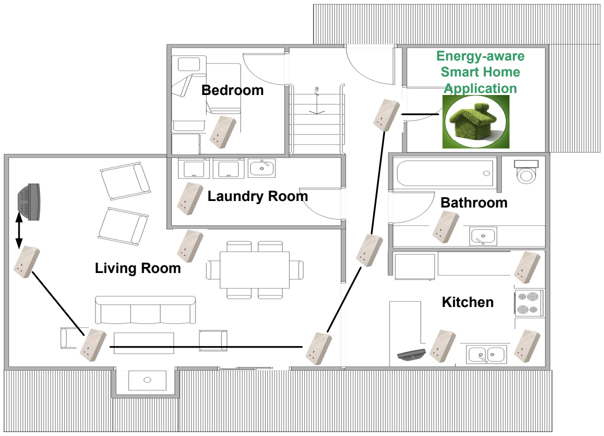

Fig. 1. A typical energy-aware smart home.

In Figure 1, a typical deployment of Ploggs inside an energy-aware smart home is shown. These smart meters use their multihop communication abilities to inform the resident about his electricity footprint. In the figure, five hops are needed from the meter that acts as the base station, to reach the meter which monitors and controls the television. Plogg discovery is automatic, based on the ZigBee specifications.

We exposed the functionality of the Web Home framework as a RESTful interface and we developed a client application in JavaScript, using the Google Web Toolkit (GWT). The client application offers a Web-based, interactive graphical user interface (GUI), in order to help residents to visualize their energy-aware home environment and fully manage their electrical appliances through the Web.

Detailed, real-time consumption data from each electrical appliance and the aggregation of historical data about energy into graphs, facilitate the extraction of informed knowledge about the home's energy performance, encouraging the habitant towards more rational usage of electricity.

In Figure 2, a typical snapshot of the client application can be observed, where the electricity footprint of each appliance is depicted in a pie chart. Through detailed energy monitoring, electricity-wasting actions can be avoided and energy-inefficient devices can be managed better or be replaced.

Through the Web, each appliance can be individually controlled. For example, the resident from his work may switch off the television he forgot on, when he hastily left the house.

Furthermore, our application enables the resident to associate the energy consumption of his electrical appliances with the actual tariffs from his electric utility, translating kilowatt hours (kWh) into money. Based on these tariffs, the electricity cost consumed by each appliance is automatically calculated.

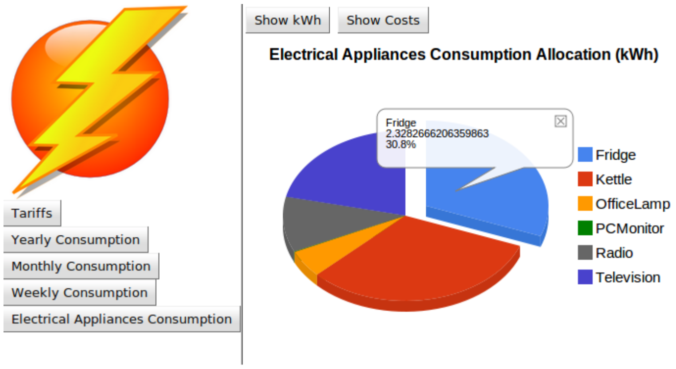

Fig. 2. Detailed electrical appliances' consumption allocation.

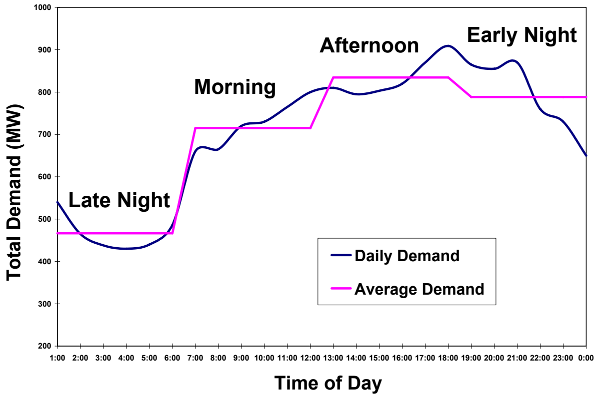

Fig. 3. Total electricity demand in a typical winter day.

A. *Exploiting Demand Response*

As we previously noted, a significant feature of the grid is DR. DR would assist in offering dynamic tariffs, according to supply conditions. Dynamic tariffs can be received in real-time, when utilities provide Web APIs to automatically disseminate them to the homes of the consumers. Since not many countries provide yet such capabilities, we also let the resident define himself the existing local tariffs.

The DR capability would allow users to cut their energy bills by telling low priority devices to harness energy only when it is cheapest. We included a task scheduling mechanism adapted to DR from electric utilities, following the physical mashup paradigm. The residents are able to program actions to be executed automatically in low-tariff hours. A low tariff is specified as a lower percentage from the basic tariff, which is offered by the utility. As an example, the resident can program the electric water heater to heat water for a shower, when the tariff is 10% less than normally.

The resident is able to further adjust the task scheduling procedure, according to his own preferences. He can define a maximum amount of waiting time, in case tariff does not fall below the specified limit in that time window. In this case, the task can start right after. The resident can also specify the execution of a task to be performed in morning, afternoon or night time. Finally, he can set the duration of each task, forcing the application to switch the corresponding electrical appliance off, as soon as the task completes.

A DR-based task scheduler can have a psychological factor. Energy-aware smart homes and the introduction of the smart grid in the residents' daily lives, can engage them in more sustainable lifestyles and energy-efficient practices [18]. The potential for saving energy and money can cultivate informed, actively involved and environmentally-aware consumers.

V. TECHNICAL FEASIBILITY STUDY

In this section, we examine the feasibility of our approach from a technical perspective.

We have deployed inside an experimental smart home of around 100 m^2, a wireless network of Ploggs. The typical structure of the house is shown in Figure 1. Our application has been installed on a laptop inside the storeroom.

Since our country does not yet support the smart grid, we simulated its operation through the Web. We developed a Web server that simulates DR functionality for the Electricity Authority of Cyprus (EAC) [19], which is the only utility in the country. A RESTful Web service informs customers in real-time about the utility's current tariffs using RSS Web feeds.

These tariffs, although simulated, aim to reflect the actual energy loads and demands in our country. Figure 3 presents the total electricity demand in Cyprus, at a typical winter day. We assume that the power plants of EAC are able to operate in four different modes for generating electric power. These modes reflect the average electricity demands when dividing a winter day into morning, afternoon, early night and late night. These four modes can be observed in the figure.

To produce real-time tariffs, correlated to electricity demand patterns, we used the simple equation shown in (1):

$$Tariff = \alpha \cdot BasicTariff \cdot \left(\frac{InstantDemand}{AverageDemand}\right) \qquad (1)$$

where α is a coefficient used to weight the prices according to differences in demands. Using this equation with $\alpha = 1$, we produce real-time tariffs that give incentives to consumers to utilize their electrical appliances not in peak hours. These tariffs fluctuate around the (current) basic home tariff, which is offered by EAC (20,07 cent/kWh), as shown in Figure 4.

To test the performance of our system, we considered a typical real-life scenario. Most washing machines allow a user to define a preferred operation mode and start the washing in a future time. We programmed such a washing machine through the task scheduling mechanism, to start the washing when the tariff from the electric utility is 5% less than its normal price. According to Figure 4, this would happen at 4:00, 7:00, 14:00 and 23:00 in a typical winter day. We also set some parameters such as the duration of the task to be one hour and 30 minutes and the maximum waiting time to be eight hours. We measured the execution times of this task, placing the washing machine and its corresponding Plogg, in different hops from our application (base station).

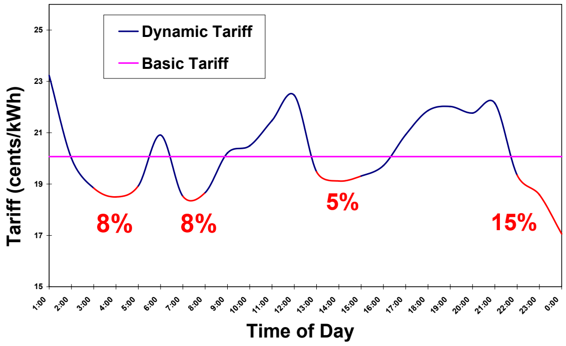

Fig. 4. Real-time tariffs based on electricity demand.

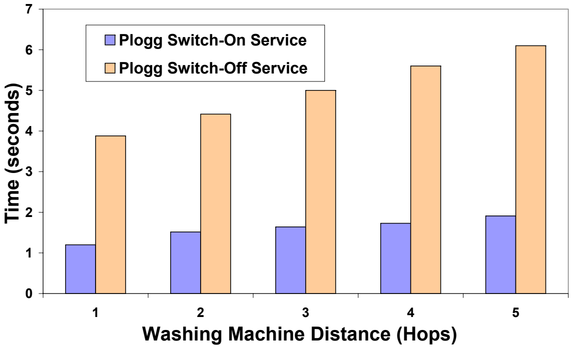

Fig. 5. Task scheduling performance.

Figure 5 illustrates the results of this experiment. In all five multihop scenarios, we created the task at 12:00, it started executing exactly at 14:00 and it finished execution at 15:30. Less than two seconds are needed, from the time the application is informed about the tariff change, until the washing machine starts working, even in five-hop distance. Switching off the device needs a bit longer, approximately 4-6 seconds. This difference is due to the specific operation of the Ploggs' firmware. Since the task scheduling mechanism will operate for control scenarios with low workload, our results in regard to task execution times, are considered satisfactory.

VI. POTENTIAL SAVINGS

Connecting energy-aware smart homes to the smart grid, creates a new potential for saving energy and money. We attempt to estimate this potential, considering that household appliances account for 50-90% of the residential consumption.

We define home devices into three broad categories. *Permanent devices*, which should never be turned off such as a fridge, *on-demand devices*, which are utilized by home residents spontaneously, in order to accomplish a momentary task such as a toaster and *schedulable devices*, which are devices that are supposed to accomplish some specific task but their operation is not momentarily urgent and can be postponed for a future time such as a dishwasher.

We are mostly interested in schedulable devices as they are devices that can be programmed to operate during low-tariff periods of the day. These devices can fully harness the DR feature of the smart grid. Therefore, electric utilities can save energy by better managing their load conditions and residents can save money by using electricity when it is cheapest.

A. A Survey for Schedulable Devices

We performed a small-scale, telephone-based survey to identify schedulable electrical appliances. We discussed with twenty housewives and we posed to them the following question: ”if your electric utility offered cheaper tariffs at some hours of the day, which tasks, handled by your electrical appliances would you schedule for these hours?”. We also asked them about the duration of each task per day, translated into operational time of the relevant appliance and also the monthly frequency, in which they perform this task.

Their responses are listed in Table I. We used average values for task duration and monthly frequency. These values depend on many parameters such as weather conditions (electric water heater), number of family members (electric iron, washing machine), mentalities and habits of each society (electric oven, dishwasher) etc. Surely, these values are not absolute but just indicative, in order to facilitate our purpose of roughly estimating possible savings through our approach.

Observing the table, we can notice that some devices can be categorized both as schedulable and on demand (hair dryer, electric mixer, electric oven). Eight housewives commented that they were willing to use such devices according to low-tariff periods, in case this would save them significant money.

B. Calculations for Money Savings

After identifying home schedulable devices, we located some popular products for each device type and we recorded their energy consumption in kilowatt-hours (kWh). We computed the average values to derive typical consumption figures.

For our calculations, we used the typical home tariff offered by EAC (20,07 cent/kWh). In the last three columns of Table I, we can view possible savings for schedulable devices, when home tariff falls 10%, 20% or even 30%.

Devices such as the electric mixer do not contribute in money savings and there is no need to schedule them for future time. However, devices such as the washing machine and the electric oven could contribute more effectively, allowing monthly savings of more than €1 each, when tariff falls 10% and more than €4, in case tariff falls 30%.

If we apply our optimized policy for all electrical appliances, monthly savings can be summed around €6 in 10% tariff reduction and up to €19 in case of 30% reduction. Considering the fact that the average monthly cost for electricity in houses around Cyprus is €175, possible saving of €19 gives 10,85% reduction in the bill of a typical home.

A survey from Parks Associates [20] remarks that over 80% of US households would pay up to $100 for cost-saving equipment if it chopped at least 10% off their monthly electricity bills. This survey indicates a possible acceptance of our approach by home residents. This is only valid under certain conditions such as effective tariff reductions by utilities.

TABLE I
A LIST OF SCHEDULABLE ELECTRICAL APPLIANCES AND POSSIBLE SAVINGS.

Device	**Consumption (kWh)**	**Duration**	**Monthly Frequency**	**Tariff Reduction in €**		
				10%	**20%**	**30%**
Hair Dryer	2.1 (1.5 - 2.5)	35 minutes	25	0,63	1,27	1,9
Electric Mixer	1.3 (0.8 - 1.5)	20 minutes	8	0,07	0,14	0,22
Electric Iron	2.8 (2.4 - 3.0)	2 hours	8	0,93	1,85	2,78
Electric Oven	2.7 (2.5 - 3.0)	60 minutes	26	1,45	2,91	4,36
Electric Water Heater	3.0	30 minutes	20	0,62	1,24	1,86
Dishwasher	1.5 (1.3 - 2.0)	40 minutes	22	0,46	0,91	1,37
Washing Machine	2.6 (2.0 - 3.0)	1 hour 40 minutes	16	1,44	2,87	4,31
Clothes Dryer	3.6 (3.0 - 4.3)	50 minutes	11	0,68	1,37	2,05
Total Possible Savings				**6,28**	**12,56**	**18,84**
Plug-in Hybrid Electric Vehicle	3.3	8 hours	10	5,46	10,93	16,39

As we remarked before, an example killer application of the smart grid might be PHEV. It would be essential for the healthy operation of the grid to force residents to charge their PHEV in low-demand periods of the day, e.g., during the night. The last row of Table I shows possible savings when a typical PHEV exploits real-time pricing. We assume that a typical PHEV needs approximately eight hours of charging in 3.3 kWh and provides driving range on batteries up to 150 miles. Therefore, it would need charging every 3-4 days to adequately support the needs of a family. In this case, monthly savings can be more than € 10 when the tariff is reduced by 20%.

VII. CONCLUSION AND FUTURE WORK

Demand response is a promising capability of the smart grid. Energy-aware smart homes can exploit this functionality, using the Web as an integration platform. This seamless interconnection has the potential for significant energy and money savings, both for the electric utilities and the customers, allowing Web-enabled smart appliances to schedule their execution for low-demand and respectively low-tariff periods.

Few people predicted the revolutionary advancements the Internet has brought to the world. Even fewer have predicted that the Web would affect so many aspects of our lives. Energy-aware smart homes and the smart grid, represent the extension of this trend to power consumption.

In the future, we plan to perform a small-scale deployment of our Web-based, energy-aware home infrastructure in real houses around Cyprus. In cooperation with EAC, we will try to simulate the DR feature of the grid in realistic conditions. In this way, we will be able to extract more precise estimations about energy and money savings and to assess the overall influence of the smart grid in the society.

VIII. ACKNOWLEDGMENTS

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