Integrating Web-Enabled Energy-Aware Smart Homes to the Smart Grid

Andreas Kamilaris*, Yiannis Tofis†, Chakib Bekara‡, Andreas Pitsillides* and Elias Kyriakides†
* Department of Computer Science
Networks Research Laboratory
University of Cyprus
P.O. Box 20537, Nicosia, CY 1678, Cyprus
Email: kami@cs.ucy.ac.cy, andreas.pitsillides@ucy.ac.cy
†KIOS Center for Intelligent Systems and Networks
Department of Electrical and Computer Engineering
University of Cyprus
P.O. Box 20537, Nicosia, CY 1678, Cyprus
Email: tofis.n.yiannis@ucy.ac.cy, elias@ucy.ac.cy
‡ Fraunhofer FOKUS Institute
Kaiserin-Augusta-Allee 31, D-10589
Berlin, Germany
Email: chakib.bekara@fokus-extern.fraunhofer.de

***Abstract*—Energy conservation is a global issue with great implications. High energy demands and environmental concerns force the transformation of electricity grids into smart grids, towards more rational utilization of energy.**

Embedded computing and smart metering transform houses into energy-aware environments, allowing residents to make informed choices about electricity. Web technologies are successfully used for managing heterogeneous home devices, facilitating the remote management of the house through Web APIs. Hence, the Web, as an ubiquitous and scalable platform, is suitable for interconnecting energy-aware smart homes and the smart grid.

In this paper, we investigate the possibilities created when energy-aware smart homes communicate in near real-time with the smart grid and we propose an architecture for their flexible integration to the grid, through the Web. A proof of concept deployment is performed and general security aspects are discussed. The potential of this Web-based architecture is demonstrated by developing two applications that exploit these new capabilities of smart homes, towards an intelligent grid. Demand response is harnessed to schedule electricity-related tasks for future execution and load shedding is employed to reduce the total load for avoiding outages. Finally, issues such as peak leveling, fault tolerance, billing and a market for energy are briefly discussed.

***Keywords*-Smart Home; Smart Grid; Web; Web of Things; REST; Smart Power Outlets; Demand Response; Load Shedding; Security.**

I. INTRODUCTION

Increasing energy demands, depletion of natural resources and rising costs make energy conservation a universal problem 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% [2].

This high energy demand cannot be accommodated by current electricity grids. Most of the electricity grids around the world have been built many decades ago, to meet the energy requirements of the society at that time. They are being incrementally upgraded, but these upgrades may not be completely adequate for the future grid, in addition to the green concerns.

Increasing demand and environmental concerns influenced initiatives towards a more rational utilization of electrical energy. This goal can be best 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, supported by two-way digital communications and a smart metering system, in a fault-tolerant, secure and more reliable manner. This vision is believed to convert traditional electricity grids into modern *smart grids*. A smart grid[1] is a network of networks that has come to describe the future electricity grid, enhanced with Information and Communication Technology (ICT), applied to generation, delivery and consumption of electric power.

Electricity smart metering involves measuring the consumption of electrical energy in frequent intervals and communicating that information at least daily back to the utility for monitoring and billing purposes. Smart metering 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 world's total electrical energy [3]. This fact has a significant environmental impact, as more than 30% of all greenhouse gas emissions is attributed to buildings.

Lately, residential smart meters have been introduced in our lives as sensor devices that measure in small time intervals

---

[1] http://smartgrid.ieee.org/ieee-smart-grid

the energy consumption of a house. In the near future, smart appliances would take advantage of the smart grid's functionality to synchronize their operations with its current state. For example, they may respond to pricing signals and decide when it is most economical to operate. An intermediate step before utilizing smart appliances could be the use of smart power outlets, which are devices that measure the consumption of electrical appliances and control their operation in real-time. In general, the practice of equipping home area networks (HAN) with smart meters, smart appliances and smart power outlets, enables the development of *energy-aware smart homes*.

Undoubtedly, these new technological advancements of HAN offer new possibilities for effective energy management and conservation. The capabilities of being informed about the domestic electrical consumption in (near) real-time and being able to control the electrical appliances of a house remotely, enable novel applications to be developed for saving energy. Especially, when combined with the operations of the smart grid, these capabilities could offer great potential towards a coordinated, large-scale plan for energy efficiency.

Nowadays, smart home solutions are vendor-specific and heterogeneous, employing various hardware and software technologies to achieve home automation. This trend is expected to continue in the future. Hence, in order to enable the smart grid vision, a common ground needs to be specified, a common language understood by all HAN, facilitating in-home and home-to-grid communication. We anticipate that the Web, as a highly scalable, pervasive and flexible platform, is an appropriate solution for such a wide-scale interconnection.

Reusing well-accepted and understood Web principles to interconnect heterogeneous embedded devices, built into everyday smart things, is the vision of the *Web of Things* (WoT) [4], [5]. It is about using the Web as a standard, to assure interoperability in resource-constrained, pervasive spaces. The concepts of the WoT have also penetrated in smart home environments, in which the performance of Web-enabled home devices is considered acceptable [6], [7].

The main contribution of this paper is to provide the architecture for the integration of energy-aware smart homes to the smart grid via the Web, emphasizing on the smart home environment, and also to demonstrate potential applications based on the proposed platform. An energy-aware smart home is deployed using smart power outlets and its remote management is enabled through the Web. The emulation of a smart grid scenario allows the (near) real-time Web-based communication between the HAN and the grid. As security is a crucial topic in this initiative, a section is dedicated on explaining in general how the whole system can be secured.

Through this proof of concept deployment, some interesting applications related to the smart grid are investigated, from an energy-aware smart home perspective. More specifically, the dynamic pricing program of the grid is exploited to schedule electricity-related tasks for the future and load shedding is studied, as a technique to reduce total consumption for avoiding outages. Furthermore, other possible applications such as peak leveling, fault tolerance, automatic billing and a distributed electricity market are discussed.

We note that in this paper the focus is on the ICT infrastructure that could be used for enabling flexible, reliable and efficient integration of smart homes to the grid. The proposed architecture targets the non-critical systems of the power grid. It is recommended that the Supervisory Control and Data Acquisition (SCADA) system of the smart grid should be on a separate architecture/network. A SCADA system is an industrial control system used to monitor and control electrical power transmission and distribution.

The rest of the paper is organized as follows: Section II presents related work concerning mainly projects dealing with the integration of smart homes to the smart grid, along with background information about the smart grid and energy-aware smart homes. After, Section III explains the reasoning why the Web could constitute a suitable platform for this integration. Then, in Section IV the development of an energy-aware smart home using Web techniques is described and in Section V our approach for connecting HAN to the smart grid through the Web is discussed. Afterwards, Section VI considers end-to-end security in the whole Web-based infrastructure while Sections VII and VIII investigate potential applications that can be developed when enabling (near) real-time interaction between smart homes and the grid. Finally, Section IX concludes the paper and defines future work directions.

II. RELATED WORK

In this section, the state of the art is presented regarding projects that aim to interconnect energy-aware smart homes and the smart grid. In addition, some background information is provided about the smart grid and energy-aware smart homes in general.

A. Building the Smart Grid

The smart grid is expected to modernize current electricity grids by providing advanced functionalities such as advanced management and control, high power quality, immediate failure alarms, fault localization and response to disturbance (self-healing), reliability, security, resilience to natural disasters and improved customer service.

An important characteristic of the smart grid is timely pricing, which is a smart energy pricing scheme that is set for a specific time period on an advance basis, and 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, based on a short-term demand forecasting, allowing them to vary their energy use in response to these prices and manage their energy costs by shifting the operation of some electrical appliances to a lower tariff period. This mechanism is mainly known as demand response (DR).

Numerous pilot projects that implement the smart grid in an experimental basis, taking into account the domestic environment, have appeared lately. We list below some of these projects, emphasizing on aspects that concern the interaction of the grid with energy-aware smart homes.

A popular project is the SmartGridCity[2], performed by Xcel Energy utility supplier in the area of Boulder, Colorado. During this project, Xcel Energy has installed approximately 23,000 smart electric meters at the customer premises, managing to collect energy usage data wirelessly and inform the customers in 15-minute intervals about their electrical consumption.

Masdar City[3] aims to be the world's first zero-carbon city, powered entirely by renewable energy sources. Pilot residences are equipped with smart meters, DR-enabled smart appliances and building management systems. By means of this infrastructure, an integrated citywide distributed management system would be created, which manages the electrical load on the grid. As an example, smart appliances are expected to customize their operation by signals received from the grid, in order to reduce the total grid's energy demand. Currently, Masdar City operates with six buildings. The city is expected to have 40,000 residents and 50,000 commuters by 2025.

BeyWatch[4] is a European project aiming to design, develop and evaluate an energy-aware, flexible and user-centric smart home solution, able to provide interactive energy monitoring for white goods, intelligent control and power demand balancing at home, block and neighbour level. ZigBee-enabled smart plugs are used for communication between home agents and the home appliances. A home agent is a middleware, implemented using OSGi service bundles, which allows seamless device/service discovery and is used mainly for energy monitoring and device control.

The Smart-A project[5] intends to consider to what extent it is possible for smart appliances to adapt their operation to variations in the energy supply. The focus is on common household appliances and, for each appliance, its operation and energy demand are modeled and its options for load shifting are analyzed. In this way, the impact on appliance design and potential service is assessed. This project offers useful results that may be used for more analytic approaches regarding operations of the smart grid such as load shedding.

The work in [8] presents various security and privacy issues arising from a smart home/smart grid interaction, the vulnerabilities of the advanced metering infrastructure (AMI) and the employed ontologies (sensors, smart meters, telecommunication protocols) as well as requirements and potential solutions to the underlined challenges. This work discusses security issues in general, while the security aspects we consider in Section VI focus mainly on a Web-based environment.

Finally, the SmartHouse/SmartGrid project[6] focuses on the interconnection of smart homes and the smart grid, proposing an Internet-based interconnection by means of big Web services (WS-*) [9]. It is suggested that service-oriented architectures (SOA) are suited for integrating smart houses to the grid [10]. The role and architecture of smart meters as well as their security and business implications are additionally discussed [11].

Similarly to [10], we argue that Web services are suitable for this integration and we move one step further by developing an experimental energy-aware smart home that is synchronized with the smart grid through the Web. We believe that REST [12] constitutes a more appropriate technique in embedded computing and for smart home solutions [13], and it is nowadays mature enough, also to be employed for the communication needs with the smart grid.

Our work differs from related work by proposing a RESTful, truly Web-based architecture for integrating smart homes to the smart grid. Our proof of concept smart home deployment, using smart power outlets and a reliable application framework for smart homes, along with the development of two energy-related applications, demonstrate the potential of interconnecting smart homes and the grid through the Web. The proposed architecture offers advanced flexibility and interoperability among heterogeneous smart home solutions, respects the privacy of customers by giving them the opportunity to actively participate in the smart grid operations while security aspects may be effectively addressed by using the Web as a platform.

B. Towards Enabling Energy-Aware Smart Homes

Residential smart metering has the potential to transform 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 residential smart meters where the home connects to the power grid. Such products include Wattson[7] and Current Cost[8]. Numerous efforts tried to analyze smart metering data to identify the energy consumption of household appliances. As an example, Marchiori et al. [14] used circuit-level power measurements to separate aggregated data into device-level estimates, with an accuracy of more than 90%. Additionally, ViridiScope [15] placed 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 advances, monitoring the energy consumption of each electrical appliance and controlling its operation becomes possible. Device-specific techniques plug smart power outlets in individual electrical appliances. Some power outlets even offer wireless networking capabilities, extending the residential smart metering infrastructure into a robust wireless network.

ACme [16] is a high-fidelity AC metering network that uses wireless sensor nodes, equipped with digital energy meters to provide accurate energy measurements of single devices. Energie Visible[9] visualizes in real-time the energy consumption of electrical appliances in a Web-based interface. In the Energy

---

[2] http://smartgridcity.xcelenergy.com/

[3] http://www.masdarcity.ae/en/

[4] http://www.beywatch.eu

[5] http://www.smart-a.org

[6] http://www.smarthouse-smartgrid.eu

[7] http://www.diykyoto.com/uk

[8] http://www.currentcost.com/

[9] http://www.webofthings.com/energievisible/

Aware Smart Home [17], users can use their mobile phones as ”magic lenses” to view the energy consumption of their appliances, just by pointing on 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, to take local decisions and intelligently control the use of household electrical appliances, in order to save energy and money [1]. Towards this direction, an appliance scheduling approach to allow appliances to coordinate power use so that the total demand for the home is kept below a target value is investigated in [18]. In addition, an optimization technique to reduce the share of the appliances in the energy bills and to reduce their contribution to the peak load is presented in [19].

In this paper, an experimental energy-aware smart home is enabled, using smart power outlets to manage the operation of the domestic electrical appliances. Our work differs from related approaches by employing a RESTful, Web-based application framework for smart homes [6], [7], which guarantees the reliable and efficient performance of the power outlets, offering even support for prioritized requests (e.g., from the smart grid). The smart power outlets become enabled to the Web through the framework and multiple family members may interact with them in real-time.

III. USING THE WEB AS AN INTEGRATION PLATFORM

The Web could constitute a suitable platform for bridging energy-aware smart homes and the smart grid. Through the Web, smart homes can be fully synchronized to the grid.

The Web is highly ubiquitous, flexible and it scales particularly well. A Web-based approach would guarantee high interoperability between heterogeneous smart grid technologies and components, and also between different smart home solutions and embedded sensor and actuation devices.

Most houses offer Internet connectivity nowadays, while technological advancements in mobile telecommunications such as LTE, 3G and WiMAX, permit the Internet to penetrate almost everywhere.

A. Web-based Smart Homes

Designing smart homes based on the Web principles is a recent practice. Web-based smart homes build upon the notion of the WoT [4], [5], which is about employing well-accepted Web practices to interconnect the quickly expanding ecosystem of sensors, actuators and smart physical devices.

Web-based interaction with household appliances is achieved following the REpresentational State Transfer (REST) [12], which 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 may be manipulated by the methods specified in the HTTP standard (e.g., GET, PUT, POST, DELETE), under a uniform interface. REST guarantees interoperability and a smooth transition from the Web to home environments.

REST can be appropriate for enabling a Web-based smart home, as it is a flexible, loose-coupled approach that promotes using the Web as the *actual* application layer of the system. Besides, it can be easily applied for enabling resource-constrained devices such as smart appliances and smart power outlets to the Web.

An alternative design would be by employing WS-*, as proposed in [20]. WS-* [9] are a set of complex standards and specifications for enterprise application integration. They are more standardized and they could provide enhanced security. However, since they use technologies such as SOAP/XML, they are not very efficient in home environments, especially in terms of response time and energy consumption [21]. A comparison between REST and WS-* is provided in [13].

Web integration of embedded devices can be performed either through embedding Web servers directly on them or by employing gateways. Directly embedding Web servers on physical devices is a recent development [22], [23]. Web-enabled embedded devices expose their services under a RESTful application programming interface (API), while communication is based on HTTP calls.

Enabling home devices to the Web, permits the extension of Web mashups into *physical mashups* [24]. 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.

To demonstrate the flexibility obtained by using physical mashups, we list below a PHP script that implements a physical mashup in only six lines of code, combining electrical appliances and RESTful Web services provided by an electric utility. We assume in this example that the utility exposes, as a Web API, information about its current tariffs. Offering real-time information is not infeasible for electric utilities. Recently, three utilities in California announced that they allowed their consumers to access their utility data through the Web. This initiative was called the Green Button [25].

This script checks the current *hometariff* and starts charging automatically a plug-in hybrid electric vehicle (*PHEV*) as soon as the tariff falls below the defined *LOW_TARIFF* limit.

```
<?php
$tariff=http_get("UtilityAddr/hometariff/");

if($tariff <= LOW_TARIFF){
 $req=new HttpRequest("HomeAddr/PHEV/Switch/");
 $req->setOptions(array(state=>"ON"));
 $req->send();
 $response = $http_req->getResponseBody();
}
?>
```

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.

Through the Web, residents may 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. Similarly, the smart home could offer its functionality as a Web API, allowing the utility to interact with it almost in real-time, for exchanging information and remote administration and control. These simple examples indicate that advanced home automation, high flexibility, seamless integration to the smart grid and energy conservation may be achieved, when using the Web as a platform.

B. The Web and the Smart Grid

Using the Web as the ICT platform for various smart grid operations offers numerous benefits also to the power grid. These benefits concern not only the communication with energy-aware smart homes but also some internal, non-critical, ICT-related functionalities of the grid.

A smart grid implementation that exploits cloud computing, using infrastructure as a service (IaaS) from the cloud, constitutes a cost-efficient practice for enhancing the functionalities of the grid incrementally as energy demands arise. The flexibility of cloud computing enables new capabilities to be implemented on the Web, in parallel to existing operations and systems, minimizing the impact of ongoing operations.

Existing systems can be securely integrated with new components and further be connected to users and customers, by means of the Web (see Section VI). The Web constitutes a pervasive and scalable platform for incorporating third-party and partner techniques.

Furthermore, 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.

Most importantly, a future cloud-based smart grid strategy using Web services would allow the seamless integration of Web-based, energy-aware smart homes to the grid. RESTful Web server may interconnect smart homes and the grid in a flexible, loose-coupled, interoperable manner. Since REST is a lightweight protocol, it could be used for efficient and scalable, near real-time interaction with hundreds or even millions of houses. As the Internet offers only best-effort services, real-time guarantees can not be provided. However, the current Internet infrastructure may support interactions through REST/HTTP close to real-time.

We note that WS-* could be well applied to achieve this interconnection [10]. Even though it constitutes a heavy protocol, it offers better security features, enables service contracts through WSDL and is more suitable for business applications. It is a matter of the electric utility to select the scheme it would adopt, or even if both should be offered. We argue that REST is becoming mature enough to be effectively utilized.

IV. CREATING A WEB-BASED ENERGY-AWARE SMART HOME

A lightweight, Web-oriented application framework for smart homes, providing uniform access to heterogeneous embedded devices via standard HTTP calls, was developed in [6], [7]. Central principles of the modern Web architecture were used to integrate home devices to the Web, in order to build an interoperable smart home that supports multiple home residents concurrently. By using the Web as the application layer at the home environment, following REST principles, flexible applications on top of heterogeneous embedded devices can be built with a few lines of code, facilitating home automation.

In this work, this application framework was extended to support interaction with smart power outlets. Thus, by means of the power outlets, remote control of the electrical appliances of a house could be achieved, through the Web.

Ploggs[10] were utilized as the smart outlets of our experimental smart home. Ploggs are ZigBee-based devices that incorporate wireless transceivers, based on the IEEE802.15.4[11] standard, forming a wireless smart metering network inside the smart home. Since Ploggs are programmed with a firmware that can not be easily changed, they can not be enabled directly to the Web. Thus, they are enabled indirectly through the application framework, by means of Java drivers that allow the communication with them through a RESTful interface.

Each Plogg is associated with some specific electrical appliance, for monitoring its electricity footprint and control its operation. To derive the house's total electrical consumption, a Plogg equipped with an external current transformer for loads up to 100 A was attached to the mains meter of the house.

Figure 1 depicts the general architecture of the extended smart home application framework. It follows a layered model and is composed of three principal layers: *Device Layer*, which is responsible for the management and control of the smart power outlets, *Control Layer*, which is the central processing unit of the system and *Presentation Layer*, which represents the access point to the framework from the Web, enabling the uniform interaction with the electrical appliances of the smart home over a RESTful interface.

Each time a new smart outlet is discovered, a new thread dedicated to the corresponding electrical appliance is created. A *Resource Registry* maintains the services offered by the power outlet, as well as information how to properly invoke them. A *Request Queue* is attached to each thread, to enqueue concurrent requests to it. Requests are stored in a FIFO manner and are transmitted sequentially to the device. Whenever a transmission failure occurs, the failed request is retrieved from the request queue and retransmitted. In this way, transmission failures are masked effectively and reliability is assured.

Driver module holds the technology-specific drivers for enabling communication with the smart power outlets, by sending/receiving requests to/from them. A *Web Server* allows Web-based interaction between users and the home devices. A *REST Engine*, implemented by means of Restlet[12], ensures a RESTful system behaviour.

In Figure 2, a typical deployment of Ploggs inside an energy-aware smart home is shown. These smart meters use their multi-hop communication abilities to inform the residents about the electricity footprint of each appliance. 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

---

[10] Energy Optimizers Ltd has stopped producing Ploggs.

[11] http://www.ieee802.org/15/pub/TG4.html

[12] http://www.restlet.org/

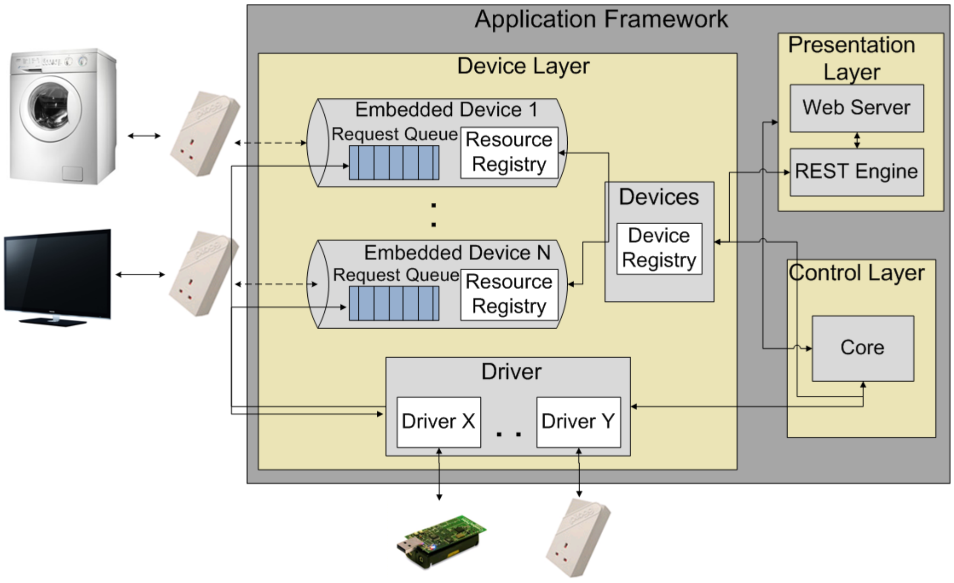

Fig. 1. The general architecture of the application framework including smart power outlets.

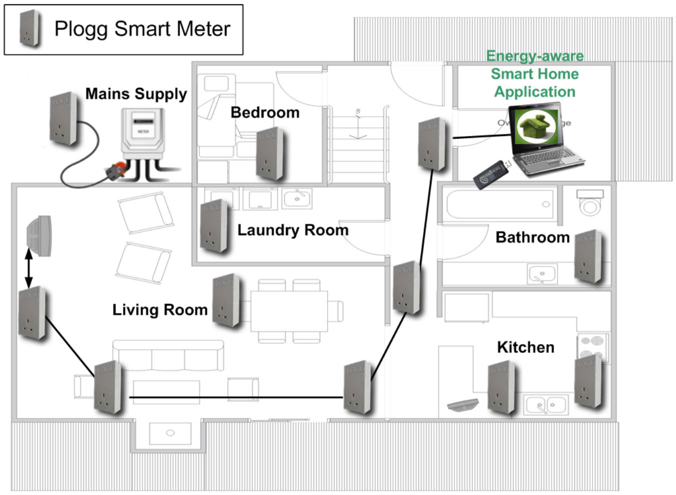

Fig. 2. A deployment of smart power outlets in an energy-aware smart home.

television. Plogg discovery is automatic, based on the ZigBee specifications. The application framework queries the wireless network of Ploggs for new devices in frequent intervals.

As shown in Figure 2, the framework has been installed on some computing device of the smart home and communicates with the Ploggs by means of a Telegesis USB stick. We must note that the framework could have been installed on the main smart meter of the house, which communicates directly with the electric utility (in a smart grid scenario) through AMI. Probably this could be the case in the near future, when main smart meters would be powerful enough to support also smart home applications and embedded Web servers.

Moreover, the functionality of the application framework was exposed as a RESTful interface and a client application was developed in JavaScript, using the Google Web Toolkit (GWT). This client application offers a Web-based, interactive graphical user interface (GUI), in order to help residents to visualize their energy consumption 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 a more rational use of electricity. Some psychological studies indicate that timely electrical consumption feedback is believed to assist in reducing electrical consumption by 5-20% [26], [27].

A typical snapshot of the client application can be observed in Figure 3, in which the electricity footprint of household electrical appliances is provided on a daily basis for the current week. Through detailed energy monitoring, electricity-wasting actions may be avoided and energy-inefficient devices can be managed better or be replaced.

Through the Web, each appliance can be individually controlled. For example, residents may switch off the television remotely from work, in case they forgot it on, when they hastily left the house. Residents can associate the energy consumption of their electrical appliances to the actual tariffs from their electric utility, translating kilowatt hours (kWh) into money. Based on these tariffs, the electricity cost consumed by each appliance is automatically calculated.

V. CONNECTING SMART HOMES TO THE SMART GRID

Connecting energy-aware smart homes to the smart grid creates a new potential for saving energy and money. Household appliances account for 50-90% of the residential consumption and their rational management is crucial for any energy conservation initiative.

The Web-based interaction between smart homes and the smart grid could be facilitated by utilizing intermediary devices called *smart grid controllers*. Each controller would be responsible for some houses or neighborhoods. More powerful

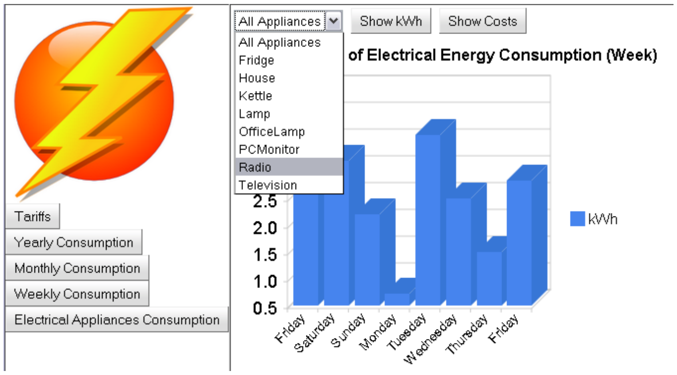

Fig. 3. Detailed electrical consumption of the electrical appliances of the energy-aware smart home.

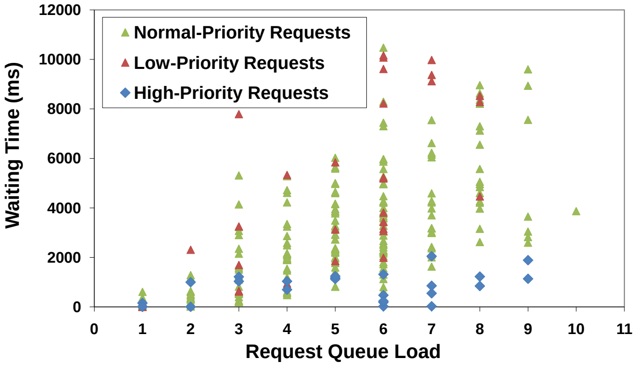

Fig. 5. The priority mechanism at the smart home application framework, showing the waiting times for requests with different priorities and heap load conditions.

grid controllers could manage larger areas such as villages and small towns. Smart grid controllers could maintain a hierarchical structure for fault tolerance and scalability. For example, controllers at higher levels (i.e., closer to the smart grid system) could be used for administering controllers at lower levels (i.e., closer to the customer premises). Low-level controllers would be able to communicate in a timely manner with each house while high-level controllers could interact with the main grid through a SCADA system. The overall system architecture is depicted in Figure 4.

We need to note that these smart grid controllers represent domestic controllers and should be separated from the main electricity infrastructure. It is also important to note that our focus is on integrating energy-aware smart homes to the smart grid, enabling flexible interaction patterns between them, and not on the operation of the smart grid and its controllers. The controllers could have specialized software for performing the grid's operations. An example implementation of a smart grid controller for emulating the behaviour of the smart grid in a scenario involving load shedding is described in Section VII-B.

As mentioned in Section III-A, the functionality of a smart home would be exposed as a Web API. Therefore, controllers can only interact with the house through the functions specified by this API. A simple Web API for Web-based smart homes, targeted to enable remote management and control by electric utilities is presented in Table I.

This API would allow the utility to get informed about the total electrical consumption of the house (*GET electricity*), ask the smart home to reduce its consumption because an outage is possible (*POST reduceconsumption*) or allow the house to increase its consumption when the total load is in safe margins (*POST increaseconsumption*). The targeted quantity of reduced consumption is specified by the parameter *reduction* and it is defined in Watts. Similarly, the maximum allowed quantity of (increased) consumption is specified by the parameter *maxincrease* and it is also defined in Watts.

The responses from these HTTP requests are in standardized formats. The POST requests for reducing/increasing consumption are satisfied through a plain-text response, indicating a ACK/NACK, while the GET request triggers a JSON response, including information such as consumption in kWh, instant consumption in Watt and a timestamp.

It is crucial for the healthy operation of the smart grid to be assured that all the HTTP calls to the energy-aware smart homes would be executed reliably and on time. Our smart home application framework guarantees the successful execution of all Web requests by using a request queue for each smart power outlet and a fast retransmission mechanism, triggered in case some transmission failure occurs in the smart home environment.

To ensure the urgent execution of the requests that are made by the smart grid, a priority mechanism may be easily included to the framework by transforming the request queues into priority heaps. Hence, requests coming from the smart grid could be labeled as ”high-priority requests”, obtaining a prioritized execution, regardless of the current load at the heaps of the smart power outlets. The waiting times for requests with different priorities in varied load conditions are displayed in Figure 5, for a typical operation of the priority mechanism in increased traffic. According to the figure, high-priority requests are executed first, with average waiting times less than a second, reaching two seconds only when the heap has a size equal or more than seven (i.e., seven or more requests waited already at the heap when the high-priority request arrived).

The functionalities of the application framework regarding mainly the fast retransmission mechanism and the support for prioritized requests are described in [28].

Respecting the privacy of the consumers, the smart home may act as a ”black box”, allowing the smart grid to make requests to assure its proper operation but, at the same time, leaving the full control and responsibility on how to satisfy these requests to the residents, aiming to maintain a high comfort level at a reasonable expense. In such a way, people's privacy and the healthy operation of the grid can be balanced.

The important question then becomes how to handle a request from the utility for reducing the overall electrical consumption. The most obvious approach would be to rely on the residents to assign priorities to their electrical devices.

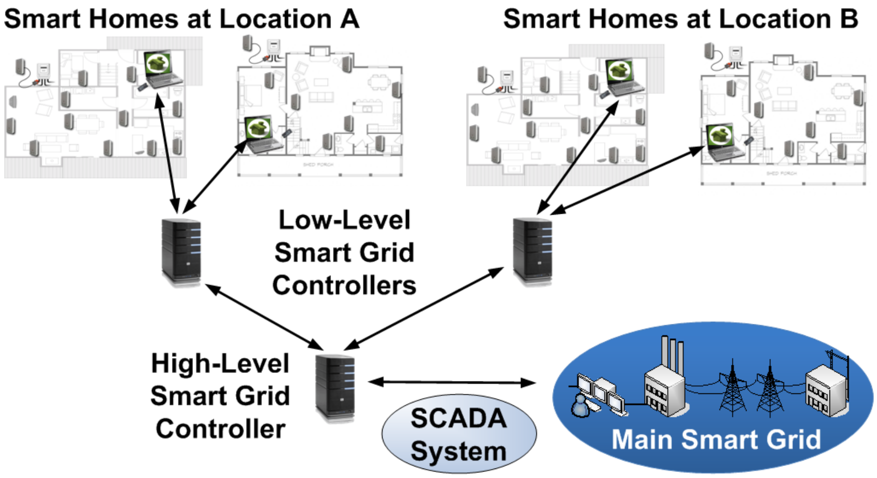

Fig. 4. System architecture for integrating energy-aware smart homes to the smart grid through the Web.

No.	Resource URL	REST Verb	MIME (Return) Type	Parameter (Type)
1	HouseName/electricity	GET	JSON	-
2	HouseName/reduceconsumption	POST	text/plain	reduction (Integer)
3	HouseName/increaseconsumption	POST	text/plain	maxincrease (Integer)

TABLE I
WEB API OF A WEB-BASED SMART HOME FOR INTERACTION WITH THE SMART GRID.

However, this may become inflexible and would complicate the whole procedure for the customers, who may have changing priorities and may not be willing to participate in such smart grid programs. An alternative approach would be to categorize devices according to their use patterns. Hence, we separate household 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 focus mainly on schedulable devices since their operation can be postponed for low-demand and respectively low-tariff periods of the day. These appliances could be immediately turned off, in case there is a prompt call from the utility to reduce urgently the domestic energy consumption.

Thus, customers are just required to identify which of their home devices are considered schedulable. Then, the application framework targets this device category to postpone use, in case there is a necessity. In the scenario when no schedulable devices consume energy and there is an urgent need for reduction, then on-demand devices would be selected.

It is trivial for the application framework to consider which devices are used on-demand, by observing their consumption patterns. Concerning permanent devices, the fridge is a special case as it could be turned off for some minutes without a problem. In addition, air conditioners and the electric heater could be special cases of on-demand devices whose operation may be postponed for some minutes.

In a complete smart grid scenario, different policies could have effect concerning the remote management of smart homes from the grid. Service-level agreements (SLA) could be used for assuring smooth supply of electricity and different customer pricing schemes could be applied. For example, ”gold customers” could pay a small extra fee for avoiding possible reduction of electrical supply in peak periods.

VI. ASSURING SECURITY IN SMART GRID-ENABLED SMART HOMES

The bidirectional Web-based communication between the smart grid and each smart home requires a trustworthy communication environment, where each party trusts the other communicating party, as well as the correctness, integrity and freshness of the received data. For instance, upon reception of pricing messages from the utility, the smart home application framework is assumed to take some actions (e.g., to charge an electric vehicle). If the pricing messages were changed on-route, the application will possibly take wrong actions. This could cause financial losses for the consumers, and even lead to a power outage (e.g., by sending fake low-cost tariffs during peak-periods).

Moreover, since the operation of smart appliances/smart power outlets must be managed by an energy-aware smart home application (e.g., to turn on energy-consuming electrical appliances during off-peak periods), it needs to be ensured that these smart devices are managed by the appropriate home application and not the application running on a neighboring home or by an attacker.

To provide secure communications for smart grid-enabled smart homes, the following basic security services need to be guaranteed:

- Authentication. Ensure the identity that another party claims to be. For instance, the smart home framework needs to be sure that it gets pricing information only from the utility.

- Integrity. Ensure that stored or received data were not modified on-route. For instance, the utility needs to ensure the integrity of metering data received from smart homes.
- Authorization. This service allows one party to verify that another authenticated party has the right to do some actions or access some resources. For instance, the smart home framework needs to be sure that a tenant requiring access to some electrical appliance has the necessary rights to do that.
- Confidentiality. Ensure that data are illegible to non-authorized parties. For instance, energy consumption sent by the smart home to the utility needs to be encrypted, such as only the utility is able to access it.
- Non-repudiation. This service prevents one party to deny sending a message or doing some action. For example. assuming that the utility sends a pricing message with a low price *Y* but applies a high price *Z*, it could not deny the fact that the low-price message was really sent by it. Furthermore, the utility needs to be sure that a consumer could not contest a bill by denying the sending of the corresponding energy consumption measurement.
- Freshness. This service protects from replay attacks, where a valid message sent at time *t*, is also sent in the future by the attacker. For instance, an attacker could replay low-tariff pricing messages during peak-periods.

Unfortunately, the Web (HTTP) does not provide a trusted communication environment, since it offers poor built-in security mechanisms and, as a consequence, needs to rely on some extra mechanisms to provide stronger security. For instance, HTTP is target to several attacks that could harm the proposed Web-based architecture, such as:

- Man-In-The-Middle (MITM) attack: An attacker successfully impersonates each communicating party (e.g., smart home framework and smart grid controller) to the other party, and injects, modifies or drops packets. This attack could target functionalities of the smart grid such as demand response, load shedding and billing, causing financial losses to both parties, and even leading to power outages.
- Man-In-The-Browser (MITB) attack: This attach involves a malicious program (e.g., a Trojan) that infects a Web browser and takes control of data entered by the user or data retrieved from the Web server and displayed by the browser. This attack could harm the user by displaying false statistics about his consumption, and not the real statistics provided by the actual smart meter of the house.
- Denial of Service (DoS) Attack on HTTP: This kind of attack aims to make a service or resource (e.g., a Web server) unavailable. For instance, this attack could target making a real-time tariff service unavailable, thus forcing the DR functionality to stop. A similar attack could be launched against the smart home framework, making grid-related operations unavailable at the victim smart homes.

A. Securing the Smart Home-Smart Grid Interaction

Securing this interaction is mandatory for making the Web-based integration of energy-aware smart homes to the smart grid in a secure, feasible and acceptable way, both for the utility and the consumers. This interaction includes exposing the functionalities/services offered by smart homes (see Table I) as Web resources, accessed and utilized by the utility. In addition, the utility exposes a set of information (e.g., energy tariffs) as resources, accessed by smart homes via the Web.

By leveraging the existing Web security mechanisms, several security issues inherent to the smart home-smart grid interaction can be addressed. Using HTTP Secure (HTTPS) [29] is one way of protecting the communications between the two parties of our architecture. HTTPS is HTTP layered over the Transport Layer Security (TLS) protocol.

The TLS protocol [30] fits between the application and the transport layer (mainly TCP), and provides a plenty of security services over the Internet, such as cryptographic key-exchange and per-session key establishment, mutual authentication, integrity, confidentiality, non-repudiation and freshness. TLS allows the establishment of a secure communication channel between a TLS-enabled client and a TLS-enabled server, in which the server is first authenticated through a certificate (optionally also the client), and then secret session keys are established using some key management protocol. Once the communication channel is established, HTTP request/response messages may be securely sent between the smart home application framework and the (low-level) smart grid controller.

In the context of a smart grid scenario, since the smart home framework and the grid controller play both the role of HTTP client/server, mutual authentication through public-key certificate is mandatory for TLS use. Each smart home obtains a pair of certified private/public keys from a trusted Certificate Authority (CA), with a strong advice to keep the private key on a smart card, onto which all public-key cryptographic operations are done, in order to avoid the private key disclosure. For reinforcing smart home security, the equipment on which the smart home framework is running should not be visible or directly accessible from the outside. Furthermore, smart homes should be protected by a separate firewall. In this way, the firewall will be the first line of defense for the smart home, while the access to the resources provided by the application framework could be easily done through redirection rules implemented at the firewall.

Finally, the smart grid controllers also obtain certified private/public keys, and securely disseminate their certificates to the respective smart homes. Similar to the smart home case, in order to protect the non-critical smart grid controllers and also the critical SCADA systems, at least a firewall protection should be employed. Nevertheless, we suggest that SCADA systems are interconnected through their own dedicated network, connected to the remaining smart grid network through gateways (integrated to or separated from the firewalls). In this way, DoS attacks may be prevented.

Since the smart home framework and the grid controllers are assumed to be hosted in powerful machines, the overheads induced by the TLS protocol (e.g., computation, transmission) could be affordable. However, if the home framework is running on the smart meter of the house, assuming that smart meters are currently resource-constrained devices, then the implementation of the whole TLS protocol could not be very efficient, because of increased memory demands and expensive TLS cryptographic operations, especially during the handshake phase for key-establishment.

B. Security Inside the Smart Home

Assuming all the in-home interactions are done through the Web, resource-constrained devices such as smart power outlets and smart appliances shall run an embedded Web server, in order to expose their capabilities as Web resources, accessible by the smart home application framework. The main challenge here is how to secure this Web-based interaction against attacks, in such a resource-constrained environment.

Generally, porting the IP stack on embedded devices is a recent achievement [31], [32]. Furthermore, Web-enabled sensor network systems in which sensor devices offer their functionalities as RESTful Web services have recently appeared [7], [22], [23]. Although these recent achievements, the WoT is not yet very common in embedded systems and constrained devices. Additionally, using standard security protocols, such as TLS or IPsec [33], does not yet constitute a popular practice in embedded computing, due to the heavy induced costs on the device operation. However, some efforts have been made recently to make these security protocols feasible for resource-constrained devices.

For instance, the Constrained Application Protocol (CoAP) [34] is a lightweight protocol for Web transfer in resource-constrained networks, sharing several similarities with HTTP. CoAP security is based on the use of Datagram TLS (DTLS) [35] or IPsec for securing the communications between the client (e.g., the smart home framework) and server (e.g., the home devices), at the transport and network layers respectively [36]. DTLS is a variant of TLS which operates over UPD (TLS operates over TCP), and which allows the establishment of a secure communication channel over which CoAP messages could transit. Due to the constrained environment of physical devices, only a subset of encryption and hash functions is assumed, in addition to the use of Elliptic Curve Cryptography (ECC) [37] instead of classical public-key cryptography (e.g., RSA, DSA), due to its low overhead in computation, storage and bandwidth.

While DTLS protects end-to-end communication (i.e., CoAP client and CoAP server), a hop-to-hop protection is also required inside the smart home, since requests and responses will probably travel through several hops to reach their destination. Since the majority of smart devices inside the home environment typically use IEEE 802.15.4 at the PHY and MAC layers, they could use the cryptographic facilities provided by the MAC layer, and in particular the AES algorithm to provide both encryption and data integrity. However, the key provisioning and key management is still an open issue, and needs to be determined at higher layers.

An additional requirement for inside-home security is the pairing. We need to guarantee that communications involve only authorized smart meters, smart power outlets and smart appliances belonging to a smart home A, and not those of a neighboring Smart Home B. In addition, smart devices of home A must be managed solely by the smart home application deployed at smart home A. Also, we need to guarantee that the smart home framework in home A controls only the home smart devices, and not those of a neighboring home B. The pairing will definitely require some level of user interaction, depending on the I/O and computational capabilities of the paired devices.

To sum up, the communication inside the smart home environment may be performed through CoAP and secured by DTLS. The CoAP request/response messages are exchanged in a way similar to HTTP, in addition to an application-level acknowledgment, since TCP is not used at the transport level for reliable data transfer. Unfortunately, as the smart power outlets included in our experimental smart home (Ploggs) were programmed with a closed firmware, they could not be enhanced with CoAP and its security mechanism. However, we strongly recommended that future real-life deployments of energy-aware smart homes need to consider protocols that provide secure communications, such as CoAP.

Finally, we need to note that we only covered some general aspects regarding assuring security in Web-based smart homes that are enabled to the smart grid. A full study, which is beyond the scope of the current paper, is required to study in detail all security issues that result in our proposed architecture.

VII. APPLICATIONS OF SMART GRID-ENABLED SMART HOMES

Here we outline some interesting applications that may be enabled when energy-aware smart homes are connected to the smart grid, through the Web. Our objective through these applications is to demonstrate the potential benefits of enabling smart homes to the grid, using the Web as the interconnection platform. Many more applications may occur in the future, exploiting more effectively the capabilities of the smart grid. This is a matter of further research.

A. Exploiting Demand Response

A significant feature of the grid is demand response. DR would assist in offering dynamic tariffs, according to supply conditions. Dynamic tariffs can be received almost in real-time, when utilities provide Web APIs to automatically disseminate them to the homes of the consumers. The DR capability would allow users to cut their energy bills by telling low priority devices to harness energy only when it is cheapest.

A DR-based task scheduler may also have a psychological factor. Energy-aware smart homes and the introduction of the smart grid in the residents' daily lives could engage them in

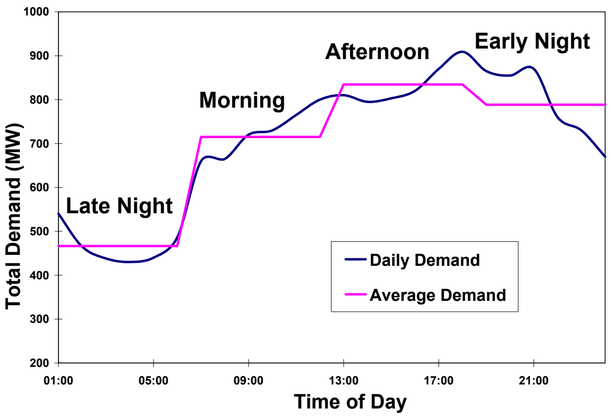

Fig. 6. Total electricity demand in a typical winter day.

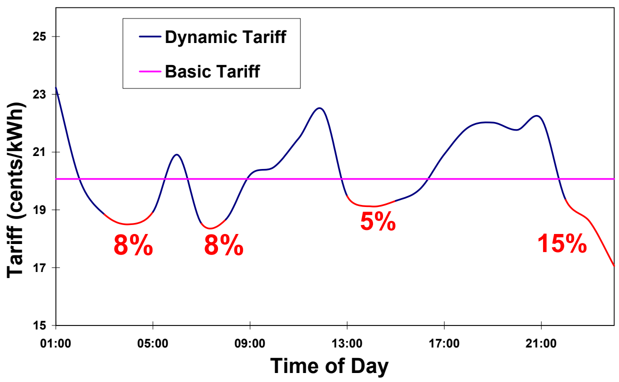

Fig. 7. Real-time tariffs based on electricity demand.

more sustainable lifestyles and energy-efficient practices [38]. The potential for saving energy and money can cultivate informed, actively involved, environmentally-aware consumers.

To demonstrate DR in energy-aware smart homes, a simulation of an electric utility offering timely tariffs was developed, interacting with a task scheduling mechanism, which was created to exploit the DR capability of electric utilities. The implementation efforts and a proof of concept evaluation procedure are described in the following subsections.

1) Implementation: We enhanced the client application, built on top of the application framework, with 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 residents are able to further adjust the task scheduling procedure, according to their own preferences. They 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 residents can also specify the execution of a task to be performed in the morning, afternoon or night. Finally, they can set the duration of each task, forcing the application to switch the corresponding electrical appliance off, as soon as the task completes.

We developed a Web server that simulates a (low-level) smart grid controller, supporting DR functionality for the Electricity Authority of Cyprus (EAC), which is the only utility in Cyprus. A RESTful Web service informs customers 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 6 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 dynamic tariffs, correlated to electricity demand patterns, we used the simple equation shown in (1):

$$Tariff = \alpha \cdot BasicTariff \cdot (\frac{InstantDemand}{AverageDemand}) \quad (1)$$

where α is a coefficient used to weight the prices according to differences in demands. Using this equation with $\alpha = 1$, dynamic tariffs are produced that give incentives to consumers to utilize their electrical appliances not in peak hours. These tariffs fluctuate around the basic home tariff, as shown in Figure 7.

2) Evaluation: 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 7, 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 the application framework (base station).

Figure 8 illustrates the results of this experiment. In all five multi-hop 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 1-3 seconds. This difference is due to the specific operation of the Ploggs' firmware.

In this experiment, we utilized Ploggs with firmware version 2.00. Comparing with the same experiment, performed in [1], where we employed Ploggs with firmware version 1.67, response time in this experiment is reduced significantly, especially for switching off some electrical appliance. This

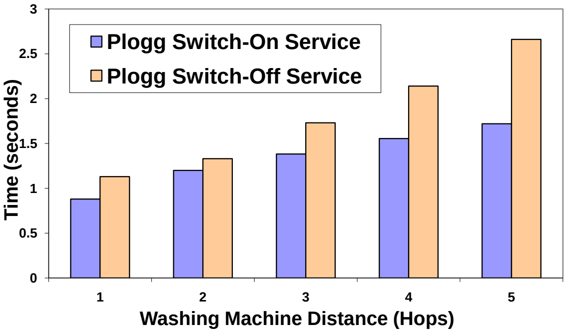

Fig. 8. Task scheduling performance.

difference occurs because data is transmitted in binary instead of ASCII form in the new version of the firmware.

Since the task scheduling mechanism will operate for control scenarios with low workload, the results in regard to task execution times are considered satisfactory.

A small-scale, telephone-based survey was performed in [1] to identify schedulable electrical appliances and their usage patterns by housewives in Cyprus. After performing some basic calculations for money savings, taking into account the average energy consumption of these appliances and the typical home tariff offered by EAC (20,07 cent/kWh), it was considered that 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 at the bill of a typical home, when our task scheduling mechanism is applied for all schedulable electrical devices. This is definitely a significant saving amount.

Finally, since many schedulable devices are used only sometimes per month or some hours per day, it is not necessary to buy a smart power outlet for each different device. By purchasing 5-10 power outlets, it may be enough to cover the daily needs of the family and schedule the operations of the schedulable devices through the task scheduling mechanism in low-tariff hours of the day. In this way, this application would constitute a low-cost investment.

B. Load Shedding

Load shedding [39] is an action taken to prevent frequency abnormal operation and is the last resort to maintain frequency stability (i.e., it retains frequency within the operational and statutory limits), in case of contingency scenarios or autonomous-islanded operation. Such a scenario could include the non-scheduled outage of a generation unit or a main transformer. In this case, the non-served load previously served by the generator that currently experiences an outage will be allocated to other online units, given that their loading can be extended, remaining within the limits indicated by the manufacturer.

However, there are two unfortunate cases that might happen. First, the online generators may not be able to accommodate/undertake the extra load because they are already highly loaded. Secondly, online generation units might be able to accommodate the extra load (because they are not fully loaded) but, depending on the magnitude of the loss of generation, the response rate of their prime movers will not be in position to accommodate such a sudden increase in load, within the time slot indicated in transmission system regulations.

In such cases, in order to avoid an under-frequency abnormal operation of the power system, the operator will be forced to apply a low frequency demand control action, removing intentionally loads from service in order to prevent the total collapse of the system due to cascading events. This procedure is the definition of load shedding and it lasts until the frequency magnitude recovers at the desired levels, when the rest of the online units are able to fully compensate the non-served load.

Load shedding is a procedure undertaken from the electric utility or the power system operator in a centralized way. The approach followed in this work is to exploit the proposed architecture and the functionalities provided by the Web APIs of Web-enabled energy-aware smart homes (see Table I), to achieve selective load shedding that can be performed in a distributed manner, providing to the grid the capability of directly controlling domestic loads. This is a major characteristic of the future grid not yet standardized and its implementation has not yet been decided.

1) Implementation: The architecture described in Section V illustrates the path of the control messages and how the control objective will be achieved, i.e., the frequency stability of the power system. Concretely, the electric utility monitors the frequency of the power system almost in real time. In the case of a critical variation based on the frequency value and its rate of change, control messages are issued from the utility control center to the high-level smart grid controllers, which order the low-level grid controllers to reduce the power consumption of the area that they are responsible for (i.e., a neighborhood). Then, the low-level controllers use the Web API of smart homes in a best-effort manner, asking the houses to reduce their consumption based on their current electricity demand and the condition of the grid.

Harnessing a smart home for these purposes has not yet been thoroughly explored by researchers and it is expected to revolutionize the future grid's structure and control. To demonstrate this potential application of the smart grid, an emulated scenario of selective load shedding has been implemented, employing three residential units in which our Web-based application framework for smart homes (see Section IV) has been deployed, along with 4-5 Ploggs at each house, associated with various electrical appliances of the house, mostly schedulable devices. The experimental setup is displayed in Figure 9.

In the scenario under consideration, it is assumed that the residential untis are located in an islanded power system. A set of generators are committed and serve the total load of the system. Without loss of generality, the system is modeled with

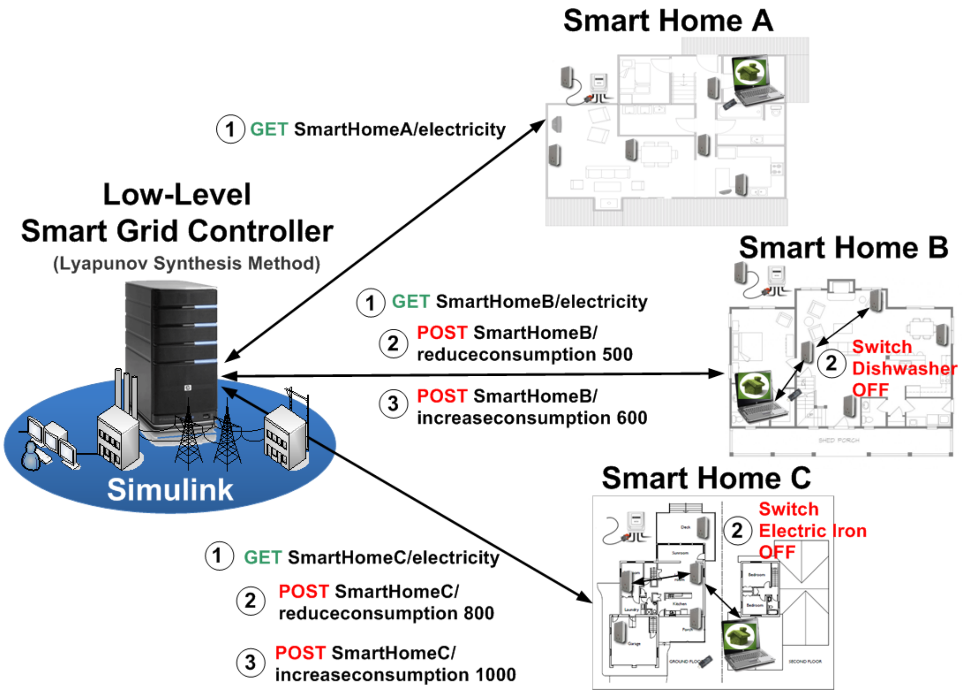

Fig. 9. The experimental setup used in the scenario of load shedding.

a generator, a transmission line and a variable load. The aim is to monitor the frequency stability of the system.

Virtual Phasor Measurement Units (PMUs) [40] have been used, which are capable of measuring both the frequency and its first derivative online in real-time.

System parameters were identified by applying the Lyapunov Synthesis Method [41], based on a simple linear second-order system frequency response (SFR) model [42]. Lyapunov Synthesis Method enables to identify the parameters of the plant by employing a suitable Lyapunov function, in terms of state variables and time, forcing this function to be at least negative semi-definite in order to obtain the desirable stability.

Further, a (low-level) smart grid controller was simulated on Simulink[13], and its main task was to maintain the stability of the system by determining the optimal (per unit) amount of electric load that should be shed to achieve frequency stability. The basic parameters of the simulation are listed in Table II.

Parameter	Value
Simulator Time Step	0.27424 msec
Total Simulation time	150 sec
Sampling Rate for Domestic Consumption	350 msec
Total Number of HTTP requests	428

TABLE II
PARAMETERS AT THE SIMULATION OF A SMART GRID CONTROLLER.

At the scenario under discussion, the grid experiences a sudden, non-scheduled increase in load. This increase has been modeled as a step function change in demand. As a result, the frequency of the power system starts to decline continuously. Three different cases are considered:

I. No load shedding takes place.
II. Load shedding is performed following the conventional practice that is applied by the vast majority of power system operators worldwide.
III. An intelligent selective/soft load shedding is performed, exploiting the proposed system architecture.

In the first case, the frequency decline is just monitored without taking any action. In the second case, circuit breakers are activated, shedding load based on an approximate rule of thumb, which indicates that the connected load magnitude should be decreased linearly in relation to the frequency decline. For example, if the frequency decreases by 1%, then load magnitude would be decreased by 2% [43]. Thus, when frequency declines 1% becoming 49.5 Hz, 2% of the load is shed. At the frequency level of 49Hz, a 4% of the initial load is shed and so on.

Finally, in the third case, the proposed algorithm was applied to determine when load shedding should be performed and the amount of load that should be shed. The current consumption is monitored in near real-time by the operator of the grid through the relevant smart grid controller, which is responsible to aggregate the consumption of the houses it controls. The grid controller obtains the current consumption by issuing an HTTP *GET electricity* command to each smart home, in regular time intervals of 100 ms. The total consumption, input to the simulated power system as a load, has been derived from the current consumption of the three domestic units, multiplied by a factor of 10,000. In this way, the emulation scenario has been scaled to an islanded grid.

Based on the total consumption, the current value of the grid's electrical frequency and its rate of change, the operator

---

[13] http://www.mathworks.com/products/simulink/

asks from the grid controller to shed the required amount of load. Then, the controller asks from each house to shed a specific amount of load by issuing an HTTP *POST reduceconsumption* command. The targeted amount of load to be shed at each home depends on its current consumption. After, the application framework decides which device(s) should be switched off based on the policy employed (e.g., according to device category and its current consumption). In this implementation, schedulable devices whose consumptions were closest to the targeted reduction were preferred to be switched off.

This is an iterative conversational procedure that takes place until the targeted total amount of load is shed. As soon as the command is successfully executed (i.e., an ACK has been received and the corresponding devices have been switched off), the simulator is fed with the scaled amount of shed load.

Finally, when the grid is in a ”safe” condition again (i.e., the frequency has recovered in normal/desired limits), the controller starts progressively to issue HTTP *POST increaseconsumption* commands to the smart homes, to gradually add the load that has been previously curtailed, allowing a maximum restoration in load at each house. Hence, the application framework switches on the schedulable devices that had been previously switched off, allowing them to finish their task.

The three different phases of the proposed algorithm can be observed in Figure 9. In this specific scenario, the grid controller monitors the electrical consumption of all the three houses and, at some time, needs to perform load shedding in order to maintain frequency stability of the system. Hence, it decides to issue HTTP POST commands to smart homes B and C to reduce their instant consumption by 500 and 800 Watts respectively. Smart Home B responds to this command by switching off the dishwasher and smart home C by switching off the electric iron. These are schedulable devices whose operation may be postponed for a future time. Then, when the system is stabilized again, the grid controller issues another POST command to smart homes B and C, allowing them to increase their consumption by 600 and 1000 Watts respectively.

2) Evaluation: Figure 10 depicts the performance of the three different schemes in regard to the time response of the frequency variation. When no load shedding is applied, the frequency declines exceeding the permitted limits (of +/- 3 Hz), causing under-frequency abnormal operation. In this case, the power grid will experience instability and cascading events will possibly follow, causing a total blackout. Furthermore, devices such as induction motors can be damaged or even burned out at low/under-frequency operation.

In the second case, when conventional practices regarding load shedding are performed, the frequency exceeds the desired levels for four seconds and needs 35 seconds in total in order to ”absorb” the disturbance. After this critical time, frequency oscillations still exist, being reduced with a small step. In this case, a set of customers would experience a total outage causing major discomfort to them.

Finally, when our intelligent selective load shedding algorithm is applied, the frequency remains at the desired levels during the whole emulation time. It recovers fast in the first 35 seconds of the emulation and totally absorbs the disturbance after 50 seconds.

Moreover, because the intelligent algorithm is sensitive even at small frequency variations and acts proactively, based on the frequency rate of change, it finally achieves a minimum total amount of load to be shed. This is in contrast to the conventional practice in which a larger amount of load needs to be shed in order to achieve the same control objective, i.e., maintaining the system frequency in the desired levels.

In addition, load restoration can be applied smoothly as soon as the frequency experiences an upward trend, exceeding a certain threshold with certain momentum (i.e., certain rise rate given by the positive time derivative of the frequency). In this way, the maximum load is restored in minimal time.

Our findings indicate that this application contributes to a more robust power grid that controls frequency oscillations in a more effective and efficient way, preventing power system instabilities and total outages of utility services. At the same time, it minimizes unexpected outages and customer discomfort by minimizing the load to be shed and by restoring it faster than the conventional practices do.

VIII. OTHER POTENTIAL APPLICATIONS

In the following subsections, some other potential applications that could be enabled using the proposed architecture are briefly described. These applications include peak leveling, fault tolerance, billing and a distributed market.

A. Peak Leveling/Shaving

Peak leveling/shaving is a process that aims to eliminate the demand in peak hours and to shift it in non-peak demand periods. In this way, the demand curve is leveled, providing maximum exploitation of the current utility infrastructure while the need for excessive spinning reserves is reduced.

For example, in the case of an expected peak hour (e.g., a world cup final), expensive generators are supposed to be employed that are able to switch on fast and follow the load changes quickly. However, this is very costly for the utility, both in operations and expenses.

The proposed end-to-end smart grid architecture will mitigate this situation by applying peak shaving, shifting the low-priority and reschedulable domestic loads to non-peak demand hours, in the way of distributing evenly the produced energy throughout the day.

The approach described in Section VII-B for load shedding could also be employed for peak shaving. In addition, demand response programs could be utilized (see Section VII-A), using special tariffs to influence consumer behavior.

B. Fault Tolerance

An important characteristic of the smart grid is the timely detection and localization of faults. The proposed architecture has been designed in order to facilitate this task through the hierarchical, distributed structure of the controllers.

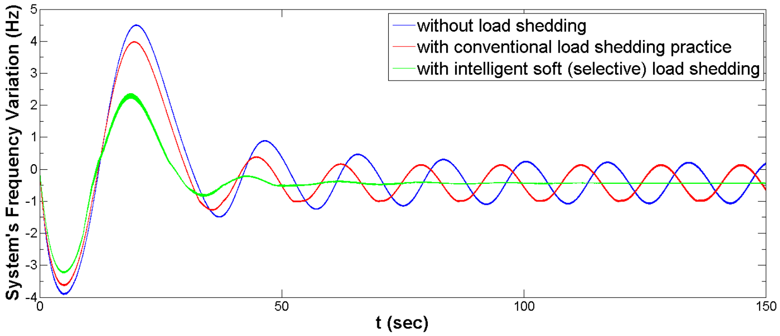

Fig. 10. Load shedding using different practices.

The established end-to-end connections between the smart grid controller and each of the smart home application frameworks provide in (near) real-time the customers' consumption. In addition, the HTTP POST requests issued by the controller, destined to the customer premises, reveal information about the status of the house, i.e., if a command has been successfully executed concerning shedding some amount of load.

In this way, the controllers can identify any abnormal behavior of the customers' consumption patterns and find out quickly which customers experience malfunctions or outages. Further, if the smart home framework does not respond to the issued commands multiple times (the customer-specific commands are re-sent until an ACK is received), this implies that the specific user experiences a failure or violates the SLA contracted with the operator of the grid.

In such cases, the smart grid controller may send some additional requests to the home framework in order to get informed about the status of the house and increase its awareness about the situation. Hence, the customers who experience unavailability of some or all services will be automatically detected and will be associated with the faulty feeders. Then, the utility crews will locate the fault and rush in immediately, reducing the duration of service unavailability (outage).

Their fast response would increase the reliability index of the company and generally improve its severity-based indices. Indices including expected unserved demand per year and expected unserved energy per year would be improved because of the faster faults restoration and the early actions taken as a result of the enhanced situational awareness of the grid.

Of course, there exist situations that could complicate fault localization. For example, a massive DoS attack on the customer premises and the smart grid controllers could hinder any efforts for fault identification and solving. Security countermeasures such as firewalls (see Section VI-A) could be employed to prevent such attacks. Nonetheless, since the proposed architecture relies on the Internet/Web, fault tolerance can not be guaranteed in general.

C. Billing

Billing is a major source of expenses by electric utilities since dedicated personnel must be employed for reading the home meters manually, requiring the physical presence of an employee at each house. The smart grid can provide long-term savings to the electric utility by providing automated meter reading via frequent interactions with energy-aware smart homes, through the Web.

Considering the Web API offered by the smart home as provided in Table I, it could be enough for the utility to issue GET requests in frequent intervals (in magnitude of seconds/minutes), to get informed about the instant domestic electrical consumption. However, this pull-based technique would not scale for millions of houses. Therefore, a Web-based push technique, such as the RESTful Message System (RMS) [44], would be more appropriate as it is based on a publish/subscribe model.

Availability of timely billing information would help residents to become more aware about their electricity footprint, giving them financial incentives to reduce their consumption.

D. A Market for Generation/Consumption of Electricity

The use of domestic renewable electricity generators could become a trend in the future. These generators would form decentralized energetic islands or *microgrids*. A microgrid consists of many small, distributed energy resources, located near each other in the low-voltage distribution system, connected to each other through some network.

Through this decentralized network architecture, smart homes may be capable of trading energy for money by means of market agents. These agents would represent electric devices, either generators (e.g., photovoltaics, wind turbines), or loads (e.g., television, fridge).

Hence, real-time auctions about electricity could be developed among energy-aware smart homes and the smart grid. According to the current generation and demand, smart homes would sell/buy electrical energy in competing prices.

The proposed architecture defined in Section V could be employed for enabling a real-time market for energy. The Web could become the platform for handling the message exchange between houses and the grid. More specifically, the Web API offered by smart homes, as shown in Table I, could be extended to support also market-related functionalities. For example, assuming that a smart home needs energy in some sunny day, its home market agent could query another smart home that generates electricity from photovoltaics, asking about the price of produced energy. This could be achieved by issuing a *GET energyprice* request. In case a deal is accomplished, this home agent could issue a *POST energy-demand* command declaring the needed amount of power. Of course, this is only a simple example, since a complete solution would require money transactions between the two parties, intelligent algorithms for automating the purchase of energy in competing prices and an infrastructure for offering the distributed generated electricity to other houses.

IX. CONCLUSION AND FUTURE WORK

In this paper, we examined the interconnection possibilities of energy-aware smart homes with the forth-coming smart grid of electricity, using the Web as the application protocol. A Web-based architecture is suggested for bridging the gap between home environments and the smart electricity grid. The Web is considered suitable for this interconnection, as it can address the heterogeneity of smart home technologies and smart grid components. Hence, advanced flexibility and interoperability is achieved by using the Web as the actual platform for the smart home-smart grid communication.

A Web-based application framework for smart homes was adapted to support smart power outlets, for monitoring and controlling the electrical appliances of the smart home. Using these smart outlets, an energy-aware smart home was deployed, allowing the remote management of home devices almost in real-time, through the Web. Reliability and prioritized requests coming from the smart grid were supported by employing request queues and priority heaps, for better handling the in-house communication with the power outlets. Moreover, a smart grid scenario was emulated, allowing the near real-time Web-based communication of the grid with smart homes by means of smart grid controllers.

The practice of connecting smart homes to the grid through the Web allows the flexible creation of various energy-related applications that target the healthy, efficient and effective operation of the grid. We demonstrated two such applications: the demand response program of the grid, for scheduling electricity-related tasks for the future, when the price for electrical energy will be cheaper; and load shedding, as a technique to reduce total consumption when danger for outages exists.

Of course, there still exist many issues that need to be addressed, before using massively the Web for this purpose. Technical issues include Web applications for smart homes that operate behind firewalls and home IP addresses that are rapidly changing. Smart home applications must conform to the Web API specifications, defined by the electric utilities. Reliability, especially inside the HAN, must be ensured. Our deployment using Ploggs showed that smart home hardware technologies are not yet mature to be used in such large-scale scenarios. We experienced regularly temporary device failures and service unavailability. These reliability issues would not be acceptable in a smart grid integration of the smart home.

Respecting the privacy of the customers is a crucial parameter for enabling a smart grid that is fully synchronized with energy-aware smart homes. Customer privacy in his home environment is reinforced through our proposed architecture by offering only a Web API to the grid, restricting the control of smart homes to the functionalities offered by this API. Considering our Web-based architecture, solely the smart home application framework can take the appropriate actions to handle grid commands, maintaining the comfort of the residents. The residents just need to specify which of their electrical appliances are considered schedulable, permitting the postponement of their operation for future time.

Security is another important factor that must be carefully considered. A satisfactory trustworthy Web-based communication environment between the smart grid and the smart homes can be assured by employing HTTPS. However, inside the home environment in which resource-constrained devices are involved, compromises need to be made to balance between acceptable performance and security. DTLS is a candidate technology for ensuring in-home security.

Our current proposal of a Web-based, RESTful architecture ensures only syntactic interoperability between heterogeneous smart home technologies and the smart grid. However, the semantic meaning of the exchanged messages is not effectively addressed by the current system. To obtain also semantic interoperability, semantic Web services may be the solution. Semantic Web services [45] are built around universal standards for the interchange of semantic data between machines. They can address issues such as advanced interoperability, automatic reasoning and knowledge inference on the smart home-smart grid ecosystem.

For future work, we plan to examine other potential applications that could be enabled when energy-aware smart homes connect to the smart grid. We also wish to validate the findings of our current applications through more detailed evaluations, including a larger number of houses and smart power outlets.

Finally, in collaboration with EAC, we plan to emulate the operation of the smart grid in a small neighborhood of energy-aware smart homes, involving also the local residents, to consider the feasibility of our proposed approach in real life and measure the actual impact of the system on the grid. Feedback from residents would be important to assess if the proposed architecture and technologies are suitable to them.

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 smart grid controllers may represent the extension of this trend to power consumption.

X. ACKNOWLEDGMENTS

This work was supported in part by the Electricity Authority of Cyprus (EAC). We would like to thank Mr Antonis Valanides, the director of the IT Department of EAC, for his valuable remarks and advice.

REFERENCES

[1] A. Kamilaris and A. Pitsillides. Exploiting Demand Response in Web-based Energy-aware Smart Homes. In *the First International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies (Energy 2011)*, Venice, Italy, May 2011.

[2] International Energy Agency. World Energy Outlook 2007. 2007.

[3] Europa Press Release. Communication from the European Commission. Energy Efficiency: Delivering the 20% target. November 2008.

[4] E. Wilde. Putting things to REST. Technical Report UCB iSchool Report 2007-015, School of Information, UC Berkeley, 2007.

[5] Dominique Guinard, Vlad Trifa, and Erik Wilde. Architecting a Mashable Open World Wide Web of Things. Technical Report No. 663, Dept. of Computer Science, ETH Zurich, February 2010.

[6] A. Kamilaris, V. Trifa, and A. Pitsillides. The Smart Home meets the Web of Things. *International Journal of Ad Hoc and Ubiquitous Computing (IJAHUC), Special issue on The Smart Digital Home*, 7(3):145–154, 2011.

[7] A. Kamilaris, V. Trifa, and A. Pitsillides. HomeWeb: An Application Framework for Web-based Smart Homes. In *Proceedings of the 18th International Conference on Telecommunications (ICT 2011)*, Ayia Napa, Cyprus, May 2011.

[8] Himanshu Khurana, Mark Hadley, Ning Lu, and Deborah A. Frincke. Smart-Grid Security Issues. *IEEE Security and Privacy*, pages 81–85, 2010.

[9] G. Alonso, F. Casati, H. Kuno, and V. Machiraju. *Web Services: Concepts, Architectures*. Springer, 2004.

[10] C. Warmer, K. Kok, S. Karnouskos, A. Weidlich, D. Nestle, P. Selzam, J. Ringelstein, A. Dimeas, and S. Drenkard. Web services for integration of smart houses in the smart grid. In *Proceedings of the Grid-Interop Conference*, Denver, USA, November 2009.

[11] Stamatis Karnouskos, Orestis Terzidis, and Panagiotis Karnouskos. An Advanced Metering Infrastructure for Future Energy Networks. In *IFIP/IEEE first International Conference on New Technologies, Mobility and Security (NTMS 2007), Paris, France*, pages 597–606, May 2007.

[12] R. T. Fielding. *Architectural Styles and the Design of Network-based Software Architectures*. PhD thesis, University of California, Irvine, California, 2000.

[13] D. Guinard, I. Ion, and S. Mayer. In Search of an Internet of Things Service Architecture: REST or WS-*? A Developers Perspective. In *Proceedings of the 8th International ICST Conference on Mobile and Ubiquitous Systems (Mobiquitous)*, Copenhagen, Denmark, December 2011.

[14] A. Marchiori and Q. Han. Using Circuit-Level Power Measurements in Household Energy Management Systems. In *First ACM Workshop On Embedded Sensing Systems For Energy-Efficiency In Buildings (BuildSys)*, pages 7–12, Berkeley, California, November 2009.

[15] Y. Kim, T. Schmid, Z. M. Charbiwala, and M. B. Srivastava. ViridiScope: design and implementation of a fine grained power monitoring system for homes. In *Proceedings of the 11th International Conference on Ubiquitous computing (Ubicomp)*, pages 245–254, Orlando, Florida, USA, 2009.

[16] X. Jiang, S. Dawson-Haggerty, P. Dutta, and D. Culler. Design and implementation of a high-fidelity AC metering network. In *Proceedings of the International Conference on Information Processing in Sensor Networks (IPSN)*, pages 253–264, Washington, DC, USA, April 2009.

[17] M. Jahn, M. Jentsch, C. R. Prause, F. Pramudianto, A. Al-Akkad, and R. Reiners. The Energy Aware Smart Home. In *Proceedings of the 5th International Conference on Future Information Technology (FutureTech)*, pages 1–8, Busan, Korea, May 2010.

[18] G. Xiong, C. Chen, S. Kishore, and A. Yener. Smart (in-home) power scheduling for demand response on the smart grid. In *IEEE PES Innovative Smart Grid Technologies (ISGT)*, pages 1–7, Manchester, UK, January 2011.

[19] M. Erol-Kantarci and H.T. Mouftah. Wireless Sensor Networks for Cost-Efficient Residential Energy Management in the Smart Grid. *IEEE Transactions on Smart Grid*, 2(2), June 2011.

[20] N. B. Priyantha, A. Kansal, M. Goraczko, and F. Zhao. Tiny web services: design and implementation of interoperable and evolvable sensor networks. In *Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems (SenSys)*, pages 253–266, Raleigh, USA, 2008.

[21] C. Groba and S. Clarke. Web services on embedded systems - a performance study. In *IEEE Workshop on the Web of Things, in Proc. of Pervasive Conference*, pages 726–731, Mannheim, Germany, March 2010.

[22] L. Schor, P. Sommer, and R. Wattenhofer. Towards a Zero-Configuration Wireless Sensor Network Architecture for Smart Buildings. In *First ACM Workshop On Embedded Sensing Systems For Energy-Efficiency In Buildings (BuildSys)*, Berkeley, California, November 2009.

[23] D. Yazar and A. Dunkels. Efficient Application Integration in IP-based Sensor Networks. In *First ACM Workshop On Embedded Sensing Systems For Energy-Efficiency In Buildings (BuildSys)*, Berkeley, California, November 2009.

[24] D. Guinard and V. Trifa. Towards the Web of Things: Web Mashups for Embedded Devices. In *Workshop on Mashups, Enterprise Mashups and Lightweight Composition on the Web, in Proc. of WWW Conference*, Madrid, Spain, April 2009.

[25] The White House. Office of Science and Technology Policy. Empowering Customers With a Green Button. Online at: http://www.whitehouse.gov/blog/2011/11/21/empowering-customers-green-button.

[26] S. Darby. The effectiveness of feedback on energy consumption A review for defra of the literature on metering, billing and direct displays. *Environmental Change Institute, University of Oxford*, 2006.

[27] G. Wood and M. Newborough. Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. *Energy and Buildings*, 35(8):821–841, 2003.

[28] Andreas Kamilaris and Andreas Pitsillides. A Restful Architecture for Web-based Smart Homes using Request Queues. Technical Report No. TR-12-5, Dept. of Computer Science, University of Cyprus, June 2012. Online at: http://www.cs.ucy.ac.cy/ResearchLabs/netrl/papers/files/kamilaris-TR-12-5.pdf.

[29] E. Rescorla. HTTP over TLS. RFC 2818.

[30] T. Dierks and E. Rescorla. The Transport Layer Security (TLS) protocol Version 1.2. RFC 5246.

[31] A. Dunkels, T. Voigt, and J. Alonso. Making TCP/IP Viable for Wireless Sensor Networks. In *Proceedings of the first European Workshop for Wireless Sensor Networks (EWSN)*, Berlin, Germany, January 2004.

[32] J. W. Hui and D. E. Culler. IP is dead, long live IP for wireless sensor networks. In *Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems (SenSys)*, pages 15–28, Raleigh, USA, 2008.

[33] K. Kent and K. Seo. Security Architecture for the Internet Protocol. RFC 4301.

[34] Zach Shelby, Klaus Hartke, Carsten Bormann, and Brian Frank. Constrained Application Protocol (CoAP), March 2012. IETF Draft, draft-ietf-core-coap-09.

[35] E. Rescorla and N. Modadug. Datagram Transport Layer Security. RFC 4347.

[36] J. Arko and A. Keranen. CoAP Security Architecture, July 2011. IETF Draft, draft-arkko-core-security-arch-00.

[37] Darrel Hankerson, Alfred J. Menezes, and Scott Vanstone. *Guide to Elliptic Curve Cryptography*. Springer-Verlag, Secaucus, USA, 2003.

[38] W. F. Van Raaij and T. M. M. Verhallen. A behavioral model of residential energy use. *Journal of Economic Psychology*, 3(1):39–63, 1983.

[39] D. Craciun, S. Ichim, and Y. Besanger. A new soft load shedding: Power system stability with contribution from consumers. In *IEEE PES PowerTech*, pages 1–6, Bucharest, Romania, July 2009.

[40] A.G. Phadke and B. Kasztenny. Synchronized Phasor and Frequency Measurement Under Transient Conditions. *IEEE Transactions on Power Delivery*, 24(1):89–95, January 2009.

[41] J. Farrell and M. Polycarpou. *Adaptive approximation based control: unifying neural, fuzzy and traditional adaptive approximation approaches*. Adaptive and learning systems for signal processing, communications, and control. Wiley-Interscience, 2006.

[42] P.M. Anderson and M. Mirheydar. A low-order system frequency response model. *IEEE Transactions on Power Systems*, 5(3):720–729, aug 1990.

[43] P.M. Anderson, A.A.A. Fouad, Institute of Electrical, and Electronics Engineers. *Power system control and stability*. IEEE Press power engineering. 2003.

[44] V. Trifa, D. Guinard, V. Davidovski, A. Kamilaris, and I. Delchev. Web messaging for open and scalable distributed sensing applications. In *Proceedings of the 10th International Conference on Web engineering (ICWE)*, pages 129–143, Vienna, Austria, July 2010.

[45] Jorge Cardoso and Amit P. Sheth. *Semantic Web Services, Processes and Applications*, volume 3 of *Semantic Web And Beyond Computing for Human Experience*. Springer, 2006.

[46] J. Franks, P. Hallam-Baker, J. Hostetler, S. Lawrence, P. Leach, A. Luotonen, and L. Stewart. HTTP Authentication: Basic and Digest Access Authentication. RFC 2617.