EnAware: A Comprehensive and Scalable Energy Management and Awareness Solution

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***Abstract*—The raising costs of energy and the increasing consumer awareness with regards to their ecological footprint poses new challenges to the industry. In a domestic context, consumers demand energy efficient products and solutions that can be seamlessly integrated and easy to use. The *EnAware* project, developed by Fraunhofer Portugal AICOS, EFACEC, EFAPEL and Bosch Termotecnologia, addresses these challenges by developing an ecosystem of interconnected smart devices. This ecosystem is composed of a smart energy meter, several smart devices and a home server. The household power meter and the home server communicate via the ModBus protocol over Power Line communication (PLC). Examples of the smart devices are smart sockets, smart switches or heat pumps. The devices communicate with the home ZigBee wireless network using the Home automation profile, which guarantees the smooth integration of third party products into the environment. The core of the *EnAware* system is the home server, which orchestrates the different devices and provides the user interface. The main differentiating factors of this solution are a set of features focusing on raising awareness on energy consumption and the scalability provided by having the service running on an OSGi platform.**

***Keywords*-Energy Awareness; Energy Monitoring; Smart Grids; Domotics; Smart Homes.**

I. Introduction

Nowadays, it is a common understanding that energy is a precious resource and its cost has been dramatically increasing. People use energy that comes from various sources and over time there have been countless social, political and mainly environmental consequences related to the use of energy. One of the main reasons for the recent environment degradation is the unconscious and unsustainable use of energy, which leads to dangerous carbon emissions to the atmosphere. The snow ball effect continues since it is proven that the climate changes are mainly due to these emissions. Unfortunately, humankind is on the end side of all this process, since we are the ones that suffer from the massive and devastating consequences of extreme climatic phenomena.

The recent increase of these climatic phenomena has been leading to several energy awareness campaigns. These campaigns aim not only at improving the Earth environment, but also at saving costs to the end user. However, these campaigns can only have a significant impact if the target audience can measure the effect of the change of behaviour and therefore be motivated to continue this change in order to optimize energy consumption even further. To effectively support these campaigns, energy management and monitoring solutions are effective tools, which should achieve the goal of providing the user with energy consumption reports that can easily provide a clear view of the energy consumption for a given period, either in a global perspective or by equipment or even aggregated by house divisions. This idea goes the same direction as the main standard management axiom stating that ”you cannot manage what you cannot measure”. Every energy management system must provide the means and results for an ongoing motivation and even education, so that the user may keep his behaviour over time. It must be stressed that usually it takes a long time to actually start enjoying the benefits of energy efficiency improvements, whereas the costs associated with them are immediate and most of the times large.

Having all these ideas and concepts in mind, Fraunhofer Portugal AICOS (Assistive Information and Communication Solutions) (FhP), in a joint collaboration with Bosch Termotecnologia S.A., EFAPEL (Empresa Fabril de Produtos Eléctricos, S.A.) and EFACEC, has enrolled in a project whose main goal is to develop a complete energy management system, with a strong energy awareness component. The system is composed of a central device (a home server in the form of a micro-PC), a smart meter developed by EFACEC, a heat pump provided by Bosch and Zigbee-enabled devices (smart plugs, switches, etc.) developed by EFAPEL. EFACEC role is to provide solutions for integrating all domestic side components with the power network, under the perspectives of Network Operation (SCADA/DMS), of Demand Side Management (DSM) and of supply of new services for the consumers. Its role will impact mainly at the level of Demand Response, specifically at Smart Metering level (smart meter, data concentrator and head-end). Bosch Termotecnologia S.A. role is to provide efficient, innovative and sustainable solutions for sanitary hot water, integrating demand response functionality. The role of EFAPEL is to provide domestic Intelligent Electronic Devices, as components for home automation, capable of local metering, improving demand response. Finally, the role of FhP is to provide human computer interaction solutions, namely for the home server, which will integrate all domestic data, interfacing the smart meter and all home components, improving demand response.

This paper describes the overall solution, starting with an introduction in Section I, followed by a detailed review of the state-of-the-art in Section II. The architecture is extensively described in Section III and some initial results are revealed in Section IV. Finally, there is room for conclusions and future work in Section V, being the last Section of the document (VI) just for acknowledgements.

II. State of the art

Energy Management and Home Automation systems are currently somehow easy to find in the market. However, the currently available products usually do not pack these two features in the same bundle and miss some of the intelligence and interoperability that would allow them to reach optimal results. The interoperability issue is even more severe as it usually means using proprietary communication protocols that limit the user to the products from a restricted group of manufacturers; in what it takes to the Energy Management features, most of the products usually do not take too serious the Energy Awareness topic, missing strong and effective data analysis and mining subsystems that would allow providing suggestions, automated actions, etc., that raises the user's energy awareness levels and reinforces his motivation and engagement in changing his energy consumption behaviour.

The systems provided by Wattvision [1], PowerWatch [2], Tendril [3] and Blue Line Innovations [4] are examples of Energy Management systems, with no focus on Home Automation or Energy Awareness features. This set of systems are capable of processing the energy measurements from the household smart meter or measuring the energy consumption of appliances with metering capabilities, and showing them, through a user friendly interface, to the user. However, the interpretation of the data is completely up to the user. Efergy [5] is another example of an Energy Management system with no major Energy Awareness abilities, but with support for remotely controlled smart sockets.

On the other hand, the systems from Vivint [6], HoneyWell [7] and TaHomA [8] are Home Automation oriented systems that are not capable of measuring energy consumptions.

Savant [9] and Alarm.com [10] systems merge Home Automation and Energy Management features into a single product. However, they are only capable of processing energy measurements from appliances, therefore they have no support for household smart meters. Additionally, and except for the activity pattern feature from [10] that can alert the user to his energy consumptions, either when he is at home or away, there is also no major focus on Energy Awareness and no energy data mining intelligent components.

Regarding Energy Awareness systems, AlertMe [11] is capable of pre-processing the measured consumption data, but has no Home Automation capabilites, having control only over smart meters and heating systems.

With a different perspective, Cloogy [12] is an Energy Management, Home Automation and Energy Awareness system. However, it is not developed with interoperability in mind, lacking the support to open communication standards and is only able to interface with Cloogy devices. The same happens with DEHEMS [13], a Framework Project 7 (FP7) project that use ”current cost” devices [14] [15] and focus an important part of its work on HCI and on system intelligence [16].

Finally, Energy@Home [17] is a Home Automation and Energy Management system supporting the ZigBee Home Automation standard, providing Energy Awareness features, i.e., it is a system that comprises all the aforementioned technologies. When compared to the *EnAware* system, it differs in the way the system intelligence is used. For example, while Energy@Home, along with the load shift dependent on demand response and floating tariffs, is more focused on the distance between the current consumption and the contracted power, or the current total energy cost and a predefined maximum value [18], the *EnAware* system is more focused on finding usage patterns and providing suggestions (for instance, suggesting scenes, detecting standby devices, etc.), as well as providing scheduling and rules support based, for instance, on actions on devices or on energy consumption levels.

EnAware, the energy management solution presented in this document, aims at raising energy consumption awareness and provides an innovative modular design that enables the easy inset of new features.

III. Architecture

Energy management technologies are evolving quite fast and there are a lot of standards, protocols, platforms and frameworks that need to be considered in order to achieve some pre-defined goals. The mindset behind the design of this solution was set in order to come up with a modular prototype that could easily be adapted to most of the scenarios. The core services were thought to be flexible enough and the peripheral modules to be replaceable or easily adapted. At the end, the system should be easy to set up and use, without compromising the grand objective: reduce energy consumption.

A. Home Server

1) Technical Details: To minimize the impact of having extra equipment at home, the Home Server was designed to run on the smallest device that could be able to meet the requirements of the project. Therefore, the choice fell on CuBox [19]. CuBox is an ARM based micro computer with an approximate power consumption of 3 W, an ARMv7 CPU running at 800 MHz, and 1 GB of RAM. These processing and power consumptions characteristics, although quite limited, were found to be enough for the project. However, the CuBox lacks on the communication interfaces needed by the *EnAware* service, namely ZigBee for the communication with the HAN devices; PLC for the communication with the power meter; and Wi-Fi so it can connect wirelessly to the home gateway (recent versions of CuBox have better specifications, including integrated Wi-Fi). To overcome these issues, three external devices were considered:

- A ZigBee to USB adaptor developed by EFAPEL and Bosch, connected to one of the available USB ports of the CuBox.
- The Linksys PLWK400 [20] was used for the PLC communication with the power meter;
- And the Belkin F7D1102az [21] Wi-Fi to USB adaptor, connected to the other available USB port of the CuBox.

Regarding the operating system, the choice ended up on ArchLinux AMR, a lightweight, flexible and minimalist Linux based operating system for ARM architectures. The *EnAware* service was developed in Java, due to its multi-platform deployment and its association with the OSGi [22] standard, which was used as the development framework. Opting for OSGi as the development framework was due to all the benefits it offers - lightweight, modularity, easy multi-platform deployment and reusable components with a dynamic lifecycle. Several implementations of this standard exist, however the choice fell over Equinox, the reference implementation of the OSGi framework, which implements all of the mandatory and most of the optional features of the OSGi R4 specification. This OSGi specification describes a dynamic module system for Java. These modules are called bundles and are possible to be installed, uninstalled, updated, started and stopped without interrupting the rest of the service or the Java VM.

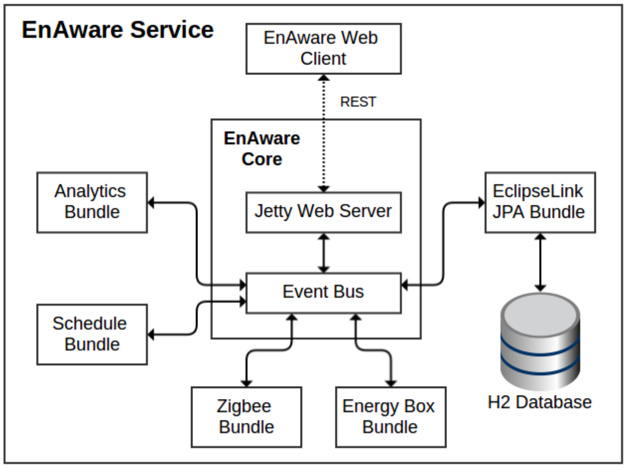

Figure 1: *EnAware* Service Architecture

Figure 2: *EnAware* User Interface

2) Client Application: The *EnAware* client application is a typical AJAX web application built upon a Fraunhofer AICOS internal Javascript framework based on the Dojo Javascript Toolkit, HTML5 and CSS. The *EnAware* web server (Jetty) has a Java Servlet for each data class and the client-server interaction follows the REST architecture (Fig. 1).

The design and implementation of the user interface aimed at meeting two main challenges. One was to provide simple interaction with all the available features and also a minimalistic but informative visualization of a potential large amount of data provided by the smart devices. The other was to have a responsive user interface, which adapts to several hardware platforms, and which might have diverse screen sizes and, at the same time, mouse or touch-based interaction. Web browser based applications are ideal for the latter challenge, as all the target platforms include a web browser and allows for multiple clients to be able to use the system without any per-client software requirements and installation. It is not a simple process to have an application that addresses a multitude of platforms, but not being restricted to a particular system is worth the challenge. When compared with more targeted applications, some compromises have to be made, for example, in interaction responsiveness. An effort was made toward minimizing these shortcomings and take advantage of what web-based applications can provide.

There is also some minimal care about security. The web portal is protected with a simple login mechanism.

The user interface has six main pages (Fig. 2). The "Home", or landing page, contains a chart displaying the current total consumption (based on the consumptions read from the household smart meter), as well as the latest system notifications and other shortcuts. The "Consumption" page allows the user to have a detailed view about all the collected consumptions. Several time intervals can be visualized, from a single day to a whole year, and the consumptions can also be aggregated by house division or by device. The "Devices" page allows the user to control the devices' status. Most of the devices can only be turned on or off, but some, like window blinds and light dimmers, can be controlled with a slider. In the "Scenes" page, the user can activate a scene or add new ones (not to be confused with Zigbee scenes, although they share the same purpose). Scenes act like shortcuts for device usage patterns. For instance, in the morning the user might frequently pull several windows' electrical blinds up and turn on the radio and the corridor light. Running a Scene executes those actions in one step. Scenes can be configured manually but the system will also automatically send recommendations when it detects frequent patterns. In the "Goals" page, the user is able to set a monthly consumption goal and check its status. Finally, "Messages" is a very simple page where the user can check all the system's notifications.

3) Core Service & Data Analytics: The *EnAware* service shares an event-driven architecture, where all the events are managed and distributed to all modules through an event bus. Most of the analysis performed have immediate results as the system receives data from the devices (stream mining), except cases in which the analysis requires data from an extended time period (for instance, Energy Efficiency Rating and Goals) and immediate results do not make sense. The analytic services were divided into three categories - Energy Measurement Aggregation, Behaviour Analysis and Energy Efficiency Rating.

The aggregation service was created mainly for performance reasons. Device measurements are aggregated into categories, to which they belong as they arrive to the system. Those categories are Timespan (day, week, month and year), House Division, Device and Total. This is an alternative to doing that aggregation when the data is requested. As a simple example, if the whole consumption from the kitchen is needed, that data is already pre-processed, so there is no wait for the whole measurements to be collected and processed.

The behaviour analysis category includes several distinct services - Device Consumption Anomaly (DCA), Goal and Scene. Within the DCA service, summary statistics are computed in a stream-like fashion to evaluate if a device is having an unusual consumption behaviour or some particular behaviour the user may be interested in detecting. One of such behaviours is if a device is standby-capable. The importance of detecting standby-capable devices comes from its non-negligible contribution to the overall consumption. According to IEA projections [23], by 2020, 10% of total appliance electricity consumption in the OECD could be for standby consumption, although there is a ongoing process

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to force the manufacturers to limit the standby consumption of their equipment to 1W (European Commission Regulation 1275/2008), being this limit lowered to 0.5W four years after the regulation inure. By detecting standby-capable devices and the most likely hours for them to be in standby mode, the system is able to suggest the user a schedule to turn them off. Other behaviours captured by this service are unusually high consumptions, devices which are on or off during an unusual schedule and devices which are on for an unusual amount of time. When such anomaly is detected, a notification is sent to the user and a relevant action upon the related devices is suggested.

The Goal service simply provides means to estimate if the energy consumption cost goal set by the user can be met, based on current and past energy consumption behaviour. The Scene service runs an implementation of the Frequent Pattern Growth algorithm, which allows the system to learn which devices are used within the same time interval. Based on this information, Scenes are suggested to the user, which can then be accepted and available for activation.

The Energy Efficiency Rating service estimates the energy efficiency class of devices based on European regulations. Knowing the efficiency class of the household appliances is another important input for energy awareness. A recent study [24] pointed out that changing to the market's more efficient appliances or the elimination/mitigation of standby consumption can reach up to 48% in savings. This efficiency estimation follows the European regulation as close as possible, but it was found that it is not feasible to strictly apply the energy efficiency calculation formulas due to their numerous parameters like, for example, dimensions or certain technical differences within the same type of appliance, which cannot be derived from the information available to this system. Even if the system would ask the user to fill in these parameters, some would require a detailed knowledge about the appliance's features, something that most users do not share. Energy efficiency is estimated by sampling the average consumption for some time period and extrapolating to the expected time period of each device class. Some device category's formulas might require the device's consumption over a year assuming a well defined usage pattern (e.g., Television, 4 hours per day during 365 days) and others for a specific operation (e.g., Washing Machine, standard washing program under full load). Nevertheless, a more detailed discussion on how this estimation is done is out of the scope of this document.

B. Zigbee Communication stack

The ZigBee technology is currently applied in several fields of the industry, e.g., health care, energy, retailing services or indoor automation to provide improved mechanisms and simplicity to ease the remote control and monitoring of activities or entities. The wide industry support is mainly due to the many standards developed by the members of the ZigBee Alliance to target custom applications. To achieve the goals of *EnAware* and meet its specifications, the Home Automation (HA) public application profile is used to communicate with all devices across the Home Area Network (HAN). The HA profile collects the required cluster set, which is a collection of commands and attributes that together define a controllable interface for a specific functionality, from the ZigBee Cluster Library (ZCL) for the *EnAware* application domains: energy metering, HVAC, switch and level control capabilities.

1) Devices: EFAPEL designed several smart devices, each with a ZigBee radio, in conformance with the ZigBee Standard and the HA profile to integrate the required functionalities. The single and dual-channel devices support one and two actuators or endpoints, respectively, in which independent home appliances can be wired to. The level control devices are capable of producing a variable output to control home appliances susceptible to level and limit control such as, e.g., window shades/blinds or dimmable light fixtures. EFAPEL has also designed a Zigbee-enabled panel with 4 programmable buttons, that is typically installed on the walls and can be used to define and trigger ZigBee Bindings (ZB), i.e. rules in the *EnAware* context, to control multiple devices at the same time. EFAPEL devices firmware also provide support for task scheduling, but do not support ZigBee Scenes (ZS). At the time of this writing, EFAPEL devices operate as ZigBee Routers (ZR), which means that they can communicate with each other by forwarding data. Further developments on device design will include devices backed by batteries that operate as ZigBee End Devices (ZED). With regards to the metering capabilities, EFAPEL devices, due to technical limitations, are not capable of obtaining consumption readings of independent channels on dual-channel devices; each reading is always, given an instant of time or time window, the combined consumption of both channels.

The Bosch heat pump version, developed within the *EnAware* project scope, is an efficient, innovative and sustainable solution for sanitary hot water production, which integrates seamlessly into smart energy technology by providing an integrated energy management system module. Common to the intelligent devices used in the project, the Bosch heat pump is equipped with a ZigBee radio, being capable of reporting energy consumption, reacting to demand response requests and adapt its energy storage conditions according to the energy cost. By using the HA profile, that gives support for the generic features through the mandatory standard clusters and the HVAC clusters - allowing, e.g., temperature set point, operation mode, water heating program - some additional proprietary clusters are used to support the heat pump smart energy integration enabling such features as: power load deballasting, load shedding, time shifting and dynamic load adjustment in function of the current tariff. Through these integrated functionalities, fine-grained control over the heat pump consumption, at any time of the day, is attained while keeping uncompromised comfort levels.

2) Home Area Network (HAN): The typical HAN in *EnAware*, depicted in Fig. 3, consists of several smart devices that talk only with the root network node, the ZigBee Coordinator (ZC), in case of ZEDs or with each other in case of ZRs for data relaying. The ZC is a USB dongle, developed by Bosch, using the ZigBee TI EMK [25], based on the TI CC2531 SoC, that is plugged to the home server and is flashed with a customized firmware developed by EFAPEL. EFAPEL additionaly designed a user-friendly case with a button for the USB dongle. The setup procedure of adding a new device to the HAN means unplugging the ZC from the home server, place it very close to the desired device and pressing the button to pair with it. The ZC will work at lower power mode when pairing with a device, otherwise it will pair with undesired devices that belong to networks in the neighbourhood. When the ZC is again connected to the home server, the list of the

HAN devices will be automatically updated.

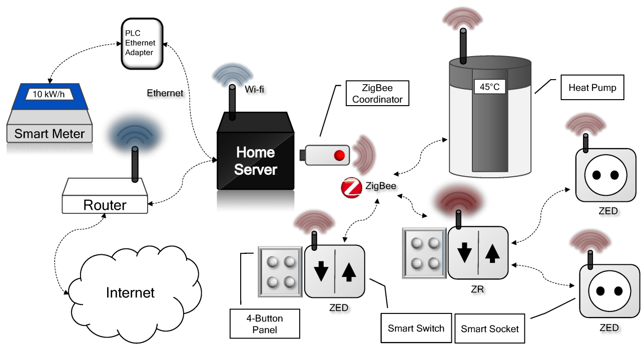

Figure 3: *EnAware* Home Area Network

3) Software layer: The ZigBee OSGi bundle is built in a modular fashion, consisting of four independent layers each implementing a bidirectional interface that enables layer crossing throughout the hierarchy. The modular architecture allows to easily extend the implementation to make the interoperability with other proprietary protocols possible, and to create new types of frames straight from factory methods. Data frames are exchanged with the ZC over a proprietary manufacturer protocol, developed by EFAPEL, on top of a serial-over-USB protocol. To accomplish this, the RXTX open source library API [26] was used as a broker to load and configure an operating system-specific native library implementation, that controls the access to the serial link.

The top layer of the hierarchy is the ZigBee service itself, that directly interfaces with the *EnAware* System core (ES). The messages, which are objects that encapsulate the content of a protocol frame, received from the ZC are processed here, its data extracted and passed on to the ES. Likewise, commands from the ES are assembled into manufacturer-dependent messages and fed to the lower layers. Layer two, the messaging layer, is responsible for managing both synchronous and asynchronous message exchanging. The protocol specifies commands that expect an acknowledge response for validation, and thus requiring synchronization, and others that do not. Moreover, consumption readings, for instance, are asynchronous messages because of their sporadic behaviour. Layer three, the data layer, extracts the payload from the message, builds a manufacturer-dependent frame and converts it to a byte buffer. Furthermore, it assembles messages by parsing raw bytes. Layer four, the serial layer, reads chunks of bytes from the serial connection data stream buffer and passes them on to the data layer.

C. Power Metering

One important part of the Home System architecture is its interface with the household smart power meter (called Energy Box), which was developed by EFACEC specifically for this project. The Energy Box is a smart meter developed having in mind the requirements of smart grids and related technology. Its communication interface is based on the ModBus protocol and uses the TCP [27] frame format.

The Home Server uses the Jamod library [28] (a Java library that supports all the variations of the ModBus protocol) to implement all the communication with the Energy Box, being able to retrieve the total energy consumption, the maximum contracted power and the smart grid demand response events, sending then all this data to upper software layers of the *EnAware* service for appropriate processing.

An important issue in the interface between the Home Server and the Energy Box is the communication medium. The Energy Box, as any other regular power meter, is usually installed outside of the house, possibly in a basement located several meters away from the Home Server. In these conditions, the use of wireless communication protocols is not appropriate, due to the interference and communication range issues that would arise. However, using wired communication may face other difficulties. Some buildings do not offer the needed infrastructures and therefore modifications would need to be done in order to install the link between these two components. To overcome these issues, *EnAware* uses the power line as the communication medium between the Home Server and the Energy Box. More precisely, from the available range of Power Line Communication (PLC) protocols, *EnAware* uses HomePlug AV [29], a PLC communication protocol developed having the home environment in mind.

D. Scalability

The discussion around the scalability of the system must be done in several dimensions. Due to the limited resources of the Home Server, the load scalability is therefore restricted and, although not yet identified but certainly high, there is a limit on the number of monitored devices and the related consumption report period. This can of course be resolved by using a more powerful server, thanks to the multi-platform characteristic of the *EnAware* service. In what it takes to functional scalability, the modular design of the *EnAware* service allows easy integration of new functionalities, which can be implemented as OSGi bundles, possibly being added or removed at any time. This means that not only the system can safely and quickly expand in features but also can easily widen the support for new devices.

IV. Performance and Results

Although the project roadmap includes some field trials, at the time of this writing they did not start yet so it is not possible to reveal some interesting results at this time, namely quantitative data regarding energy savings.

The system, mainly the Home Server, has been subject to intensive stress tests in order to assess its performance and stability. Due to its specifications, the Home Server is quite sensible in terms of CPU usage and memory consumption. The stress tests are composed of several energy consumption readings (30 devices reporting each 5 seconds) and GUI operations per second made by dummy devices. Thanks to a remote monitoring subsystem, we were able to follow to evolution of these indicators and, although they quickly reach the limits of CPU and memory capacity, they kept quite stable over time and the Home Server has been able to run smoothly without any interruption. The major overhead found is related to the persistence layer. The use of JPA with an H2 embedded database is found to be heavy for such a low-power server and if the number of events to be processed is unusually high, the system easily reaches its processing limit. Also, if the number of objects in the database is extremely large, the analytics subsystem also demands a lot of CPU and memory.

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These issues, under extreme circumstances, may have impact on user experience while using the web portal since some lag and longer response times will be noticed. Since new versions of CuBox are currently available, which feature better specifications, it is expected that the *EnAware* service can support a higher throughput of events.

V. Conclusion and Future Work

As mentioned in this document, *EnAware*, apart from being an ordinary energy monitoring and management tool, has a special focus on energy awareness by implementing some features in a way that would allow the user to not only have a clear, detailed and intuitive view of the energy consumption, but also to be continuously engaged in optimizing it, reducing costs and helping our planet. Also, the benefits of using the OSGi model, like the support for pluggable data analysis engines, are characteristics that distinguish *EnAware* from the currently available energy management systems.

Some ideas and features were already identified as future work. They can easily be added to the system by taking advantage of using an OSGi model. Top priority goes to completing the support for smartgrids, namely the support for smart tariffs and demand-side management. There is the need to widen the array of supported Zigbee devices, also adding support for more Zigbee profiles and more home automation features. Also, the service is in need of a better user management system, enabling a multi-level access control system that could allow, for instance, having some users restricted to just being able to control a subset of devices or house divisions. The concept of rules is also targeted for expansion, adding support for rules having the energy consumption as trigger. Although the system provides a web portal that can be accessed by any web-enabled device (Desktop/Laptop or any mobile device), it is planned the integration of an LCD display that will be somehow connected to the home server and is also available to display a quick view of the overall energy consumption, as well as some alerts or messages.

VI. Acknowledgements

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