Design and Evaluation of an Architecture for Future Smart Grid Service Provisioning

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***Abstract*—The increase of distributed renewable electricity generators, such as solar cells and wind turbines, requires new energy management systems where real-time measurements and communication between end users, suppliers and utilities are vital. To address this need, we propose a common service architecture that allows houses with renewable energy generation and smart energy devices to plug into a distributed energy management system, integrated with the public power grid. The presented architecture facilitates end-users to optimize their energy consumption, enables power network operators to better balance supply and demand, and creates a platform where new market players (e.g. ESCOs) can easily provide new services. This service architecture has been implemented and is currently evaluated in a field trial with 21 users, of which we present the initial results.**

***Index Terms*—Smart Grid Management, Energy Efficiency, Service Oriented Architecture**

I. INTRODUCTION

Since the emergence of the World Wide Web about 20 years ago, the Internet has become an increasingly important part of our daily lives. We now use the Internet anytime, anyplace, anywhere. The next step is the integration of smart devices that are able to communicate with each other and collaborate to improve the user experience. In such an Internet of Things a whole range of new, intelligent services becomes possible.

An example of such a domain where communication between different devices and the automatic processing of real-time measurements are needed, is the power grid, which is currently changing rapidly. It is moving away from the centralized power generation paradigm to increasingly distributed renewable power generation at residential sites, promoted by governments that are concerned about the environment. In Europe these concerns are expressed by the 20-20-20 targets [1].

However, the intermittent nature of these renewable energy sources significantly complicates balancing of demand and supply, which is essential for the correct operation of the grid. Additionally, energy demand is undergoing important changes as a result of the ongoing electrification of the vehicle fleet which generates an extra load on the grid [2].

978-1-4673-0269-2/12/$31.00 © 2012 IEEE

There is a clear need for a smart power grid where especially in the distribution network extra communication and intelligent devices are needed to ensure availability, efficiency and low emmisions. Such a smart grid is beneficial for several actors: by deploying the proper control mechanisms, the power network operator can save money by avoided investments for additional capacity. The industrial and residential customers benefit from green, locally produced power and lower energy bills by automated shifting of flexible loads towards cheaper time windows. To enjoy these benefits, an integrated ICT network for controlling (distributed) energy resources is required. This allows advanced demand response services such as peak shaving and load flattening and by moving generation capabilities closer to the consumer, transmission costs and losses can be avoided.

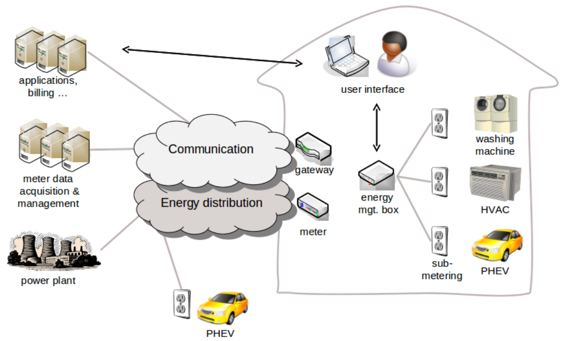

Fig. 1. Smart grid actors and components: the power grid is augmented with a communication interconnecting energy management boxes with service providers.

Furthermore, a smart grid allows the deployment of services aimed at the end-user. Such services can help the customer in reducing his energy consumption by making him aware of his consumption pattern and behavior using detailed real-time information. Such a service could be provided by a home energy management box, installed at the customers' premises and managed by a service provider. Additional smart services, also installed in the home-box, can take a more active role for example by using dynamic load shifting techniques to move controllable devices to low energy cost times.

In today's market there are already a number of end-user services available, typically providing an energy dashboard that gives detailed monitoring information on residential energy usage. For example Greenbox's CustomerIQ [3] provides an online power monitoring website and GEO's energy monitors [4], make use of displays that are installed in the residence. These solutions however lack control algorithms to steer devices in an automated way, in response to real-time information on local energy production, energy tariffs and flexibility of energy needs.

In Figure 1, we illustrate the actors and components involved in smart grid end-user services. In the home, the energy management box hosts local intelligence (local services) and is connected to a multitude of smart devices. To achieve optimal energy efficiency, the home energy box is connected through a communication network to external service providers that may offer additional intelligence.

In this paper a flexible energy service architecture based on OSGi is presented targeted at residential users to improve their energy efficiency and the easy provisioning of new services by service providers and network operators. In comparison with older smart grid architectures in the literature (e.g. [5], [6]) it offers remote deployment of new services. More recent similar architectures also based on OSGi (e.g. [7], [8]) show the potential of such a pluggable service architecture. In comparison with these platforms our architecture is not only verified in a lab setting but also deployed at the premises of 21 trial participants. The first results of this ongoing field trial are presented at the end of this paper.

II. Smart Grid Management Architecture Design

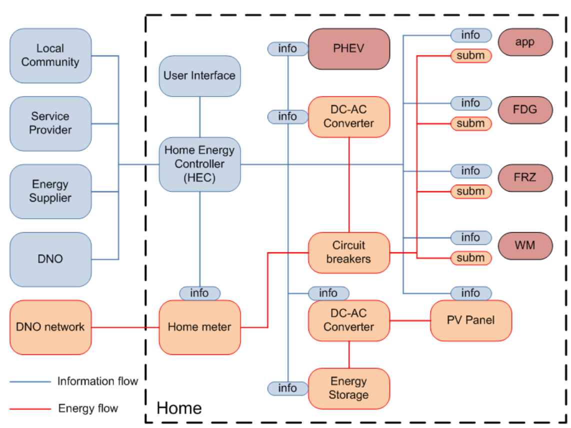

Fig. 2. High level architecture of the power grid (energy flows) and ICT network (information flow).

Figure 2 depicts the components of the developed smart grid service architecture, that comprises a power grid and ICT network. Communication between the ICT components can be provided by a mix of different physical media communication protocols such as Zigbee, power line communication, WiFi and Ethernet. All ICT modules are connected with the Home Energy Controller (HEC) which is the centralized component in the in-house energy management, and resides at the consumers premises. It can host smart applications that control and communicate with the local devices. An external communication link is also provided, for communication with remote systems of the power grid operator or of other service providers.

The HEC plays a major role in raising consumer awareness, and thereby stimulating a change of energy consumption. Information such as real-time consumption costs or comparisons with similar profile houses can be provided through an end-user GUI to the consumer.

The ICT architecture allows for service providers to deploy (Internet-based) services, such as a real time pricing service that informs customers of changes in the energy price, or demand response services that actively control smart devices. Flexible prices can help end users to change their behavior and shift consumption to periods with low consumption (e.g. at night) or with an excess of local generated renewable energy (e.g. at noon on a sunny day). As such, the typical peaks in consumption in the morning and in the evening can be reduced, relieving the distribution network operator (DNO) from investments in additional capacity and still cope with the expected increase of the total load due to the electrification of the vehicle fleet.

Direct load control signals can help energy suppliers to take care of imbalances e.g. caused by a difference between the predicted and actually generated amount of renewable energy. The DNO can use these signals to take care of voltage problems and possible power overloads (e.g. caused by excessive local generation by PV panels). This illustrates the need of not only measuring local consumption and production at end user premises, but also measuring power quality along the feeder lines and in substations. The data of all these sensors needs to be processed in an automatic and intelligent way to improve grid stability and optimize asset management.

III. Smart Energy Use Cases

The developed architecture targets especially the emerging smart energy market for residential users to help them to improve their energy efficiency. A large number of use cases were derived for this segment, which can be classified in two main categories:

- Primary use cases: use cases perceived by users as adding a lot of value to the way they use energy and in particular helping them to improve their energy efficiency.
- Enabling use cases: use cases necessary to enable the primary use cases even if not perceived by users as adding (a lot of) value. Such use cases are mostly management and billing services that often run in backend systems.

The primary use cases can be classified in 3 main categories according to increasing level of added value and of increasing potential to improve energy efficiency.

A. Raising Awareness

The use cases in this category focus on making the end user more aware of his/her energy consumption. Real-time measurements are needed of both the total household energy consumption and more detailed measurements on circuit level (room or zone) and device level for some large consumers (cooking/washing/drying machines, boiler, heat pump).

The measured information is presented to the user to increase the usage awareness and stimulate him/her to save energy. It gives the user also an idea about standby consumption. Besides consumption measurements the current and near future energy tariffs should be presented to the user if these depend on the time of the day (e.g. day tariff vs night tariff or more dynamic time of use schemes) to stimulate the user to move consumption to cheaper periods.

B. Giving Guidance

A step further is guiding the user to become more energy efficient. This can be accomplished by comparing his recent consumption with historical information to see evolutions which can have a positive impact on the motivation of the user. Comparisons with similar users (similar with respect to the type of house, the number of inhabitants, etc.) can also stimulate the user to do better. By analyzing historical information specific advice for saving energy could be derived. For example, the increasing consumption of the freezer can lead to an advice to defrost. Also unusual behaviour could be signaled such as a device that is consuming more than normal (which could be an indication of a defect or ageing of the device) or a device that is active longer than usual (which might be erroneously left powered on).

C. Automating Optimization

The most advanced set of use cases try to optimize the user's energy usage in an automatic way, taking into account the comfort level of the user. Possible automated modifications are on/dim/off actions of smart sockets and loops, adjusting temperature set points of radiators, on/dim/off actions of the heating phase of the water boiler, determining the destination of the energy produced by the photovoltaic panels (house or grid), and the optimal charging of a battery taking into account current and future tariffs.

IV. Implementation & Field Trial Evaluation

To evaluate the designed architecture and measure the added value for the end user a field trial is set up with 21 participants. This field trial started in November 2011 and will run for about 5 months. Every week the participants fill in a short questionnaire followed by a longer questionnaire at the end of every month. They will also be interviewed halfway and at the end of the trial. These questionnaires and interviews will give us an idea of how often the participants consult the application, what information they like, what information is neglected and how they change their behavior.

The HEC collects the data from the smart meter in the house and the deployed sub meters. This data can be consulted by the end user via an Android app on a smartphone or tablet. The metering data is also sent to the backend where it can be used for billing, but possibly also for more advanced use cases such as demand response programs.

The backend pushes every day dynamic tariffs for the next day to the HECs, based on the day ahead prices of the BELPEX which is the Belgian power exchange for trading in day-ahead electricity.

The HEC is implemented as a number of OSGi bundles which means that it is easy to remotely update the services or deploy new applications. Figure 3 shows some screenshots of the Android application.

Fig. 3. Some example screenshots of the Android app showing the energy consumption in the living room for this week compared with previous week (left) and the dynamic tariffs for today and yesterday (right).

The first results of the questionnaires indicate that most participants use the application rather often and try to use a similar amount of energy as the previous day. Some trial participants use the application very actively and even think to replace appliances that consume a lot of electricity. About half of the trial users take the (virtual) dynamic prices into account to shift devices to cheaper periods of the day. The shifted devices are mostly white goods such as washing machines, tumble dryers and dishwashers. To most of the participants, the submetering of a number of appliances and circuits is of great relevance. It allows them to get an idea of the large consumers in their households and it reveals their standby electricity use.

The results of the questionnaires will be combined with detailed consumption measurements which are collected by the HECs and sent to the backend, and the dynamic tariffs. This will for instance allow to compare the total consumption during expensive and cheap periods at the beginning and at the end of the field trial and compare the results for the different participants.

Figure 4 shows an example of the energy consumption of a trial participant for one day. Both his global electricity consumption as 6 different sub measurements in different rooms of the house are shown. We see a large peak in consumption in the evening and a smaller one in the morning.

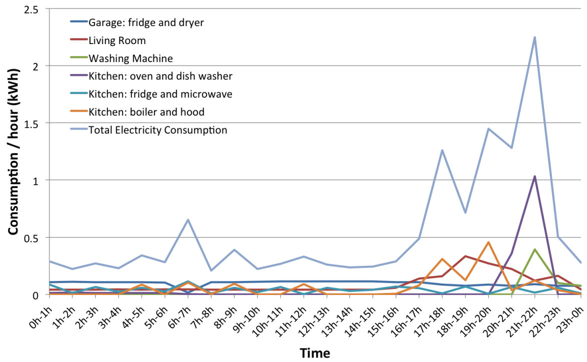

Fig. 4. Example of the energy consumption of a trial participant for one day. Both the global consumption as several sub measurements are shown.

During the day the inhabitants were probably at work or at school as consumption is as low as during the night.

When we compare the different submeasurements we see large differences depending on the kind of devices or rooms that are measured. For example the consumption of the fridges in the garage and kitchen is relatively constant over the day. In the living room there is a low constant consumption during the night and day, probably due to electronic devices in standby mode such as a TV settop box, and a considerably higher consumption in the evening with a peak around 18h - 19h. At that moment the residents are probably watching television. Later that evening we see some high peaks in consumption when the dish washer and washing machine are used.

It's clear from these observations that energy measurements are very sensitive information. They reveal a lot of the behavior of the inhabitants and could violate their privacy if this data would become publicly available. This data should therefore be handled with the greatest care and when distributed outside the home, e.g. to DNOs or energy suppliers, the added value for the end user should be high.

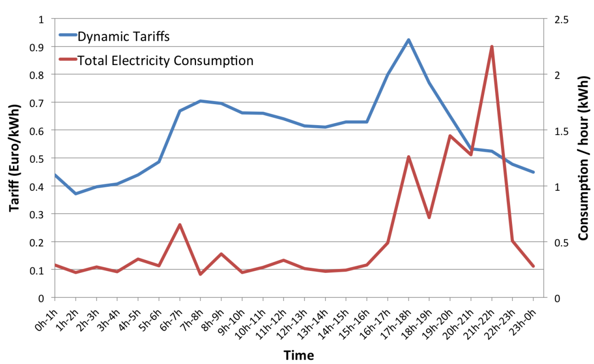

Fig. 5. Example comparison of the total electricity consumption and the dynamic tariffs for one day.

Figure 5 shows the total electricity consumption for the considered day compared with the dynamic tariffs for the same day. The tariffs are low during the night and higher during the day with an evening peak between 17h and 18h. It seems that the trial participant has taken this tariff information into account and waited for lower tariffs later in the evening to start his dish washer and washing machine.

The gathered data in the backend is very useful for power network operators and suppliers to better predict future consumption patterns and local production. This will improve network and asset management and reduce balancing costs for energy suppliers.

V. Conclusions

In this paper we have presented an architecture for service provisioning in smart grids that seamlessly integrates with the power grid, both in the power distribution network and the in-house power network. It differs from other state-of-the-art architectures in that it offers a fully integrated control system, that allows the deployment of external services and control of all smart devices that are managed by the home energy controller. The presented service provisioning architecture not only allows end-users with renewable energy sources to interact, but also supports interaction with new players in the value chain, such as energy trading services or energy brokers or aggregators.

The first results of the ongoing field trial, where the designed service architecture is deployed and evaluated, clearly show that both the end users as grid operators can benefit from the measured information.

Acknowledgment

Work presented in this paper has been supported by the Flemish Government the project SmartE (an IBBT ICON project). K. Mets would like to thank the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) for financial support through his Ph. D. grant. C. Develder thanks the Research Foundation - Flanders (FWO - Vlaanderen) for his post-doctoral fellowship.

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