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

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***Abstract*—The current Internet evolves to a true Internet of Things where a plethora of heterogeneous devices are connected, communicate with each other and allow the deployment of new intelligent services, creating new ecosystems in diverse domains. One such a domain is the power grid. The increase of distributed renewable electricity generation, e.g. 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 in diverse domains 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 that aim for a reduction in EU greenhouse gas emissions of at least 20%, 20% of EU energy consumption to come from renewable energy sources, and a reduction in energy consumption of 20% by 2020 [1].

Renewable energy sources, such as solar or wind, offer a greener solution compared to more traditional energy sources such as fossil fuels (i.e. coal). However their intermittent nature significantly complicates balancing of demand and supply, which is essential for the correct operation of the grid. Other issues of the future power grid are voltage and frequency instabilities as a result of local generation, e.g. voltage increases on a feeder line due to injected power from solar panels. Additionally, energy demand is undergoing important changes, e.g. as a result of the ongoing electrification of the vehicle fleet. Plug-in (hybrid) electric vehicles (PHEVs) require power from the grid to charge their batteries, resulting in an extra load on the grid [2], [3].

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. The benefits of the smart grid are not limited to the power network operators but reach both industrial and residential customers as well. 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 makes real-time control of energy consumption and production possible and allows the implementation of advanced demand response services such as peak shaving and load flattening [4]. Not only are high power demands steered towards high production times, the locality of the distributed generators can be exploited. By moving generation capabilities closer to the consumer, transmission costs and losses can be avoided.

Additional services in the smart grid aimed at the end-user can be deployed. Such services may lower the cost of energy by shifting loads, but could also involve the customer in the reduction of his energy consumption. By making the end-user aware of his energy consumption pattern and behavior, giving

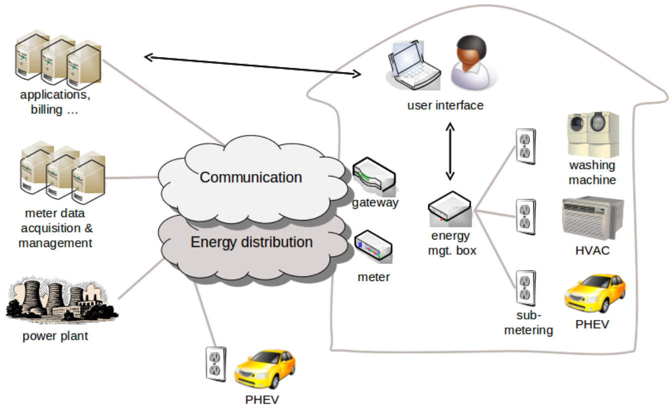

Fig. 1. Smart grid actors and components: the power grid is augmented with a communication interconnecting energy management boxes with service providers.

detailed (real-time) information on consumption, energy can be saved. 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 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: smart digital meter, a smart washing machine, a remotely controlled HVAC, a PHEV charging station, etc. To achieve optimal energy efficiency, the home energy box is connected through a communication network to external service providers that may offer additional intelligence. Additionally, service providers may offer supporting services such as billing applications, device scheduling services and realtime brokering services.

In this paper a flexible energy service architecture is presented targeted at residential users to improve their energy efficiency and the easy provisioning of new services by service providers and network operators. Furthermore the first results are presented of the ongoing field trial where the designed architecture is deployed at the premises of 21 trial participants.

The remainder of this paper is structured as follows: in section II we give an overview of the current state-of-the-art in smart energy home protocols and control services. In section III we present our smart grid service architecture that allows for dynamic deployment of new end-user services. Subsequently, a number of smart energy use cases are presented for improving the energy efficiency of residential users. Next, we discuss the set-up of the ongoing field trial and present some preliminary results. Final conclusions are summarized in section VI.

II. Related Work

A. Smart metering standardization efforts

Whereas NIST [5] is in charge of standardization of the smart power grid in the United States, the European Commission has issued a mandate M/441 to the three European standardization organisations CEN [6], CENELEC [7] and ETSI [8] to define an open architecture for utility meters and services. This mandate covers smart meter functionalities and communication for usage of electricity, gas, heat and water applications. Today, there are about 110 applicable technical standards available in the field of smart metering. However, no standard details an open architecture that covers the full application range. The mandate should ensure interoperability of technologies and applications within the European market.

The envisioned open architecture positions the smart meter gateway as central device in the home. This gateway could be part of any of the digital meters (electricity, gas, water, heat) or deployed as a separate device. Interfaces need to be defined to specify the communication with the in-home meters and home automation services. Additionally, an open interface is required to connect with one or more out of a set of service providers, offering two types of smart grid services:

- **Technical services** refer to those services that help to control the electrical grid and include smart grid stability services, smart grid security services, demand side management, etc.
- **Commercial services** are offered to the end-user and may comprise billing applications, tariff alerts, pre-payment systems, PHEV charging services, energy aggregator services, etc.

B. Smart energy end-user services

In today's market there are already a number of end-user services available. These services typically provide an energy dashboard that gives detailed monitoring information on residential energy usage. We distinguish:

- **Local in-home solutions**, which have no connection to a public communication network;
- **On-line solutions**, where the energy dashboard is connected to a service provider in the public communication network.

Microsoft Hohm [9] and Greenbox's CustomerIQ [10] are two examples that provide an online power monitoring website. Other solutions, such as GEO's energy monitors [11], make use of displays that are installed in the residence.

Both types of solutions merely provide real time information on total consumption cost and the source of the energy usage. Some of the solutions allow to switch off devices according to a given schedule. All 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.

C. Smart grid management architectures

To allow the interaction of houses with renewable energy generation and smart energy devices with the power grid, a pluggable energy services architecture needs to be designed. Other smart grid architectures have been proposed in the literature [12], [13]. The algorithm and architecture described in [13] provides a distributed control system for the electrical power structure. The micro grid management system [12], is an agent based system for the management of generation and storage devices in the low voltage grid. Both architectures lack support for remote deployment of new services.

More recently, service oriented architectures are developed within the European research projects SmartHouse/SmartGrid [14] and DEHEMS [15], focussing respectively on variable tariffs and domestic energy efficiency. The service architecture that is presented in the remainder of this paper was developed simultaneously, connecting all power grid actors and allowing an easy deployment of new end-user services in the home.

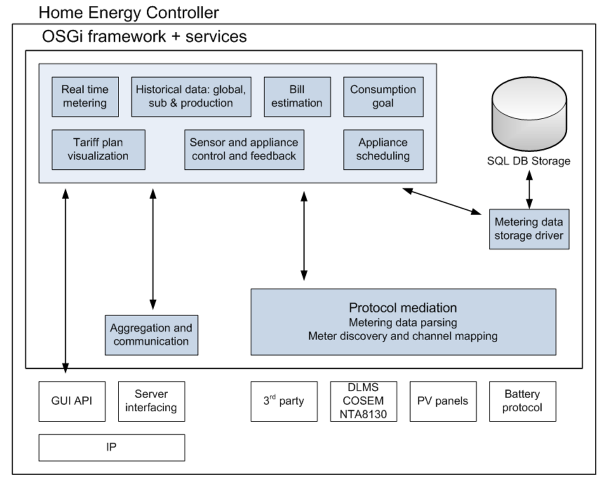

Fig. 3. Overview of the different services deployed on the Home Energy Controller (HEC)

III. Smart Grid Management Architecture Design

A pluggable energy service architecture was designed to allow the interaction of houses comprising renewable energy generation and smart energy devices, with the power grid. This flexible architecture allows the creation of a wide range of use cases, both in the power distribution network and in the in-house network. Additionally, central as well as distributed control strategies are supported. Our proposed architecture enables the remote deployment of smart energy end-user applications and control algorithms that manage renewable energy sources and provide flexible end-user services such as billing processes, PHEV charging coordination, dynamic load shifting of smart devices, etc. It is also possible to interact with other power consumers, e.g. to compare consumption patterns or exchange energy efficiency tips.

Figure 2 depicts the components of this 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.

As shown in figure 2, residential appliances, such as the refrigerator (FDG), the freezer (FRZ) and the washing machine (WM), can be provided with a submeter (subm) and an ICT enabled control module (info). The submeters provide detailed power usage monitoring support and are connected to the circuit breaker. More advanced systems such as a PHEV + DC-AC converter and solar PV panels are also supported by the architecture. If these devices do not have a built-in submeter or ICT control module, these modules can be added separately. All ICT modules are connected with the Home Energy Controller (HEC) (figure 3).

The Home Energy Controller is the centralized component in the in-house energy management, and resides at the consumers premises. This Home-box can host smart-applications that control and communicate with the local devices. An external communication link is also provided, which can be used for the communication with remote systems of the power grid operator or of other service providers.

The Home Energy Controller 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. This GUI is accessible via different media, such as an interactive touchscreen, digital TV, PC or a mobile device.

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.

Virtual aggregators are used to (virtually) group consumers in a local community based on certain criteria, such as their consumption profile, their flexibility in device shifting,

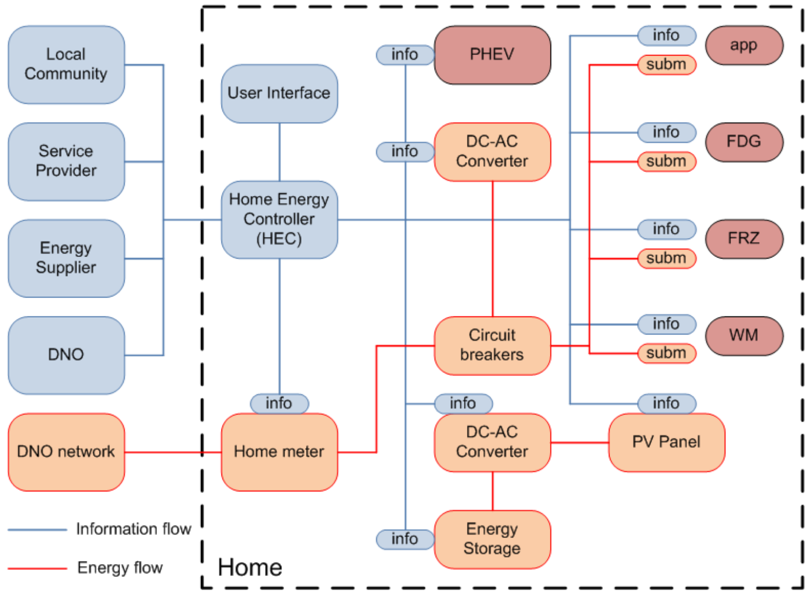

Fig. 2. High level architecture of the power grid (energy flows) and ICT network (information flow).

etc. An automated segmentation and classification method is described in [16]. The aggregated group of consumers provides extra flexibility compared to a single consumer. This provides greater optimization capabilities for smart grid services.

IV. 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.

Figure 4 gives an overview.

The primary use cases can be classified in 3 main categories (raising awareness, giving guidance, automating optimization) 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. Therefore real-time measurements are needed of both the total household energy consumption (electricity but possibly also gas and/or water consumption) and more detailed measurements on different levels such as circuit level consumption (room or zone) and device level consumption for some large consumers (cooking/washing/drying machines, boiler, heat pump). These measurements can be supplemented with temperature measurements in the different rooms of the house.

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.

All this information should be presented in a clear and intuitive way. The information could be shown on multiple devices, such as dedicated energy screens, smartphones and tablets, the television or on websites depending on user preferences.

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

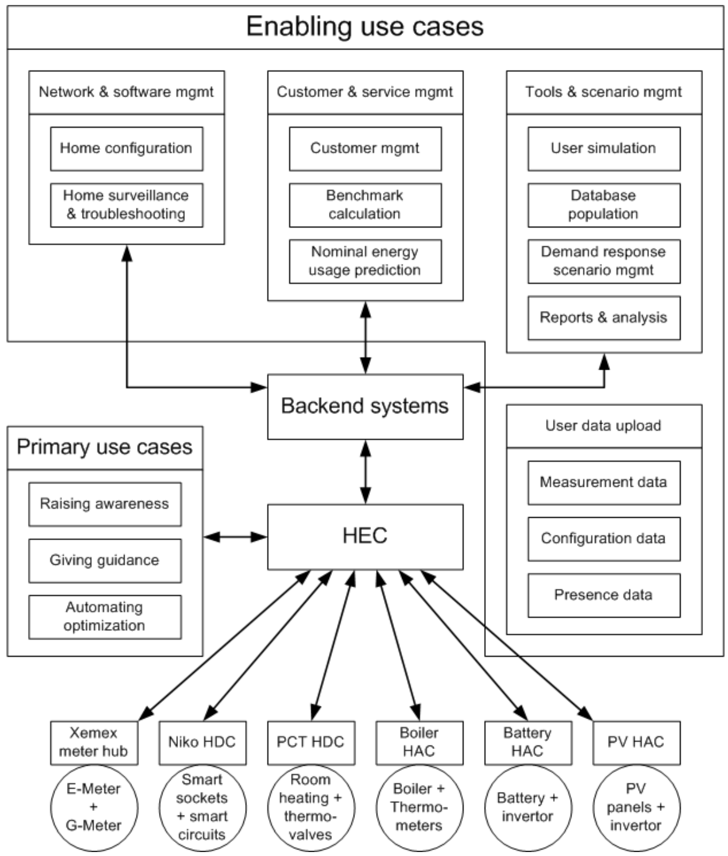

Fig. 4. Overview Use Cases.

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.

D. *Enabling Use Cases*

The enabling use cases are mostly management services that often run in backend systems. An example is customer management including billing and the prediction of the energy usage of a large group of users. Other examples are the management of the software on the HEC and the actual data upload from the households to the backend systems.

More advanced use cases such as demand response programs are not evaluated in the field trial but are equally possible. Both open loop demand response systems (where incentives or load reduction requests are sent to the customer and it is then up to him/her to decide whether to participate or not), as closed loop programs (where the customers' HECs always send a reply whether they will participate or not) are possible. Using these programs peak loads can be avoided, and imbalances and related costs can be reduced.

V. 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 questionnaire 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 taking the dynamic tariffs into account.

Figure 5 shows the architecture as it is implemented and set up for the field trial. When a HEC is installed in a house it registers itself with the backend. It gets metering 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. These tariffs are 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

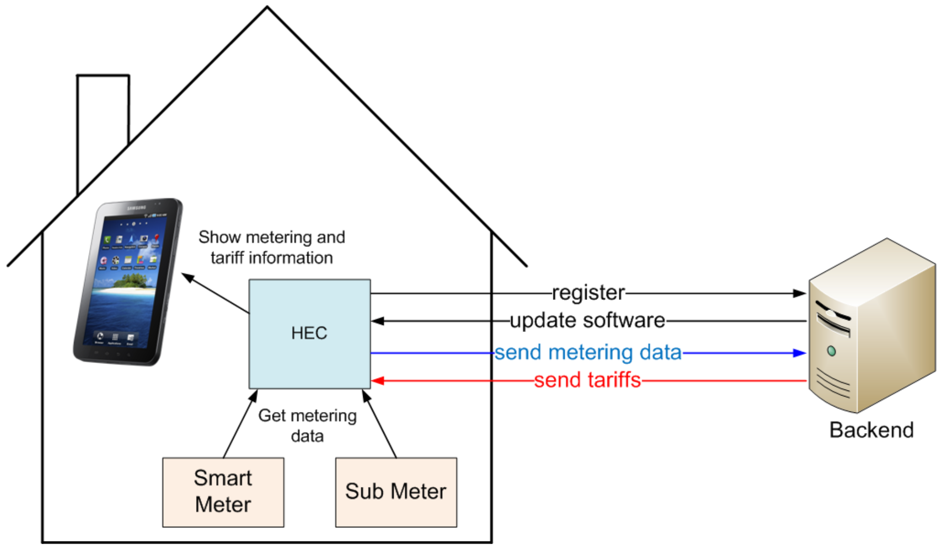

Fig. 5. Overview of the field trial set up.

which means that it is easy to remotely update the services or deploy new applications.

Figure 6 shows some screenshots of the Android application, showing the energy consumption in the living room for this week compared with the previous week (left), a comparison of the profit of the solar panels for the last two weeks (middle) 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 7 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. 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

TABLE I
TOTAL CONSUMPTION PER SUB METER.

Measured appliance/room	Total consumption (kWh)
Garage: fridge and dryer	2.34
Living room	2.14
Washing machine	0.57
Kitchen: oven and dish washer	1.48
Kitchen: fridge and microwave	1.02
Kitchen: boiler and hood	1.55
Total electricity consumption	12.97

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 behaviour 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.

Table I shows the total consumption of the different sub meters for the considered day. The total consumption of that day, 12.97 kWh, is a little higher than the average in Belgium of 10 kWh. The top consumer within this household seems to be the fridge in the garage although this is not immediately clear from figure 7. On the other, there is a high peak in the evening caused by the dish washer, but as there is no consumption during the rest of the day, the total consumption

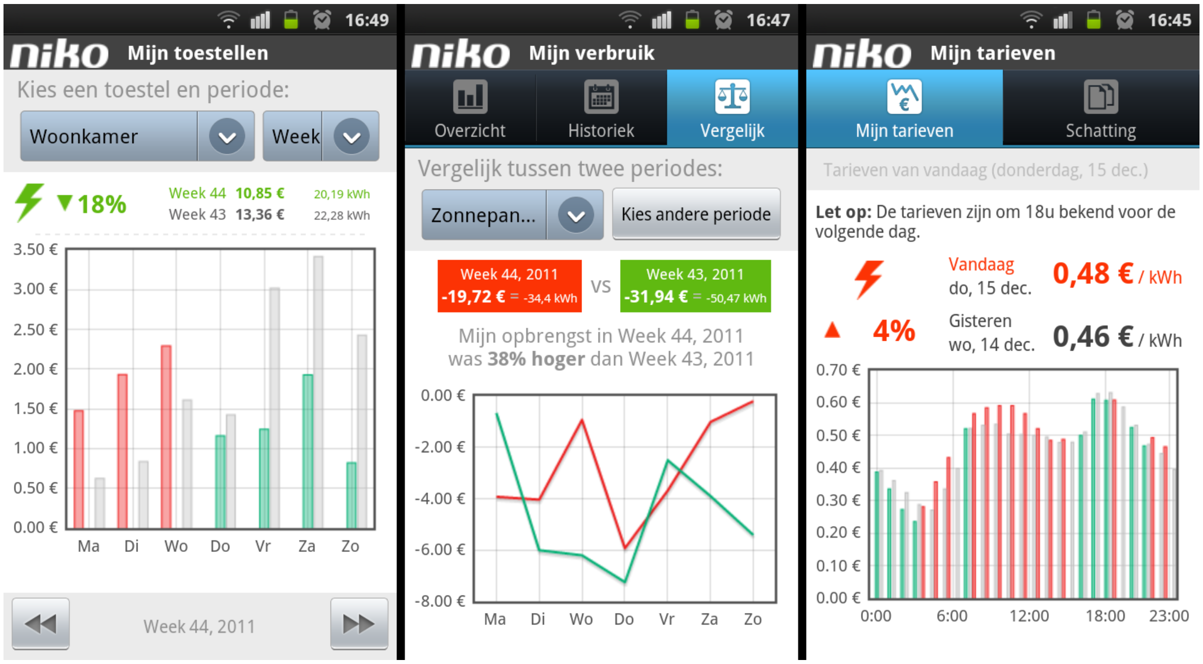

Fig. 6. Some example screenshots of the Android app showing the energy consumption in the living room for this week compared with previous week (left), a comparison of the profit of the solar panels for the last two weeks (middle) and the dynamic tariffs for today and yesterday (right).

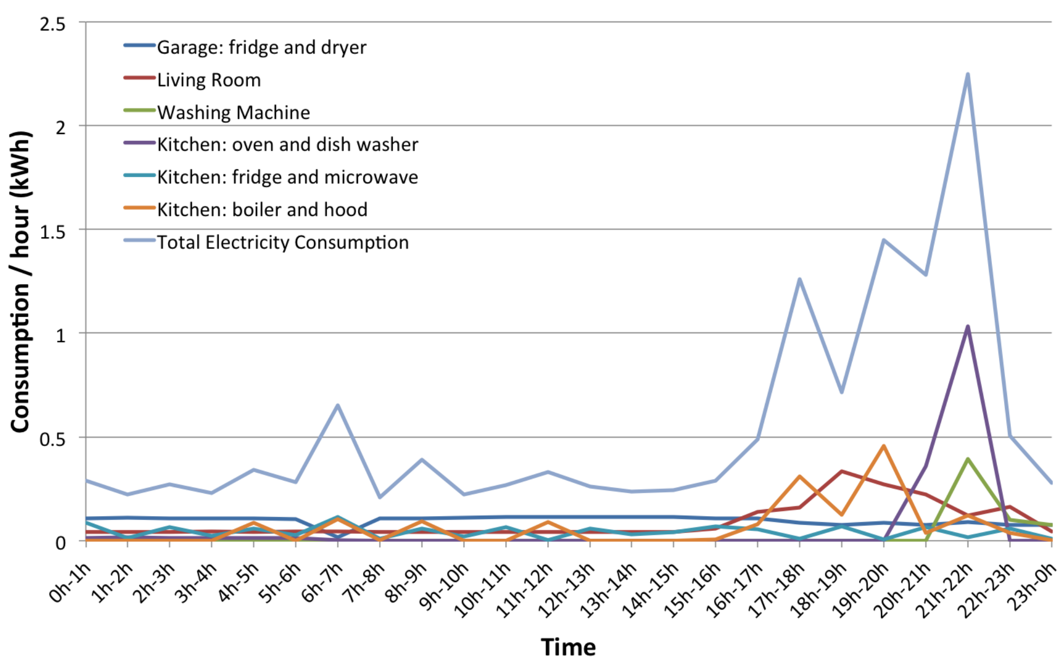

Fig. 7. Example of the energy consumption of a trial participant for one day. Both the global consumption as several sub measurements are shown.

of this device is not that high.

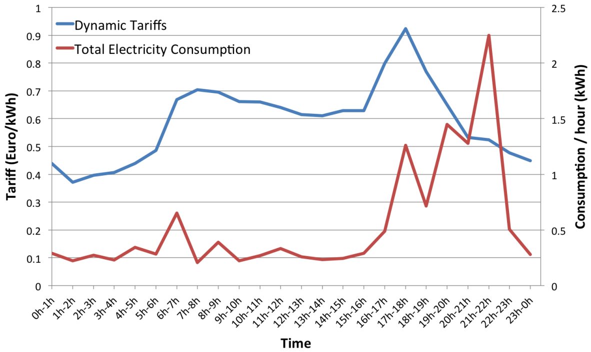

Fig. 8. Example comparison of the total electricity consumption and the dynamic tariffs for one day.

Figure 8 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.

VI. Conclusions

In this paper we have presented a 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. The architecture allows end-users with renewable energy production (wind, solar) and with shiftable loads to get involved in more rational energy consumption patterns, and to participate in the local balancing of energy demand and supply.

The architecture 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. Local communities can be created by grouping end-users based on certain criteria. The presented service provisioning architecture not only allows end-users with renewable end-users 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.

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