Sensing in Power Distribution Networks via Large Numbers of Smart Meters

Dejan Ilic, Stamatis Karnouskos, and Per Goncalves Da Silva

***Abstract*—The electricity grid is undergoing significant changes as it paves its way towards a smarter grid. New technologies provide a much clearer view on the electricity grid and its processes, mainly due to the fine-grained and near real-time acquisition of data as well as assessment of it. The huge amount of information will include additional technical data beyond the traditional metering information for billing purposes. This may give rise to a new generation of tools that rigorously monitor residential end-points. Such monitoring may assist towards rapidly identifying problems and decrease the time to resolve them. Currently, a real-time view of the grid state is done by specialized equipment, but their costs combined with their need to be widely deployed, is a limiting factor. Today's modern communication approaches coupled with high-performance analytics can be used in complex system monitoring and assessment. We argue how a large network of distributed smart meters can be used for analytics of the smart grid, based on our experiences in developing a smart metering platform that is currently monitoring approximately 5000 real smart meters. We analyse and discuss the results stemming from the data being streamed to the platform, and show how new insights can be obtained with respect to power quality.**

***Index Terms*—energy management, information management, smart grids, web services**

I. Introduction

WE are witnessing a paradigm change taking place in the electricity grid, as the infrastructure is empowered by modern information and communication technologies that enable bidirectional interactions among its participants [1]. This is expected to have profound impact on existing business aspects associated with the grid and its stakeholders. The rapid evolution of networked embedded devices [2] has significantly enhanced the monitoring [3] and management capabilities in the network itself. Due to the increased fine-grained information acquisition as well as the high quality and frequency of it, we are moving towards real-time view of the whole network. Such capabilities also empower traditional approaches for estimating the network state to analyse it down to the device level.

The ageing infrastructure will require significant investments in order to cover renovation and reinforcement required in near future [4]. Both ageing and expansion make the state estimation in such networks a challenging aspect. The latter is mainly due to lack of real-time measurements, especially at lower voltage range [5]. While Supervisory Control And Data Acquisition (SCADA) systems e.g. in UK generally extend only down to $33kV$ networks, on $11kV$ such systems are seldom available [5]. Therefore pseudo-measurements are introduced for estimating the system state. Still, the system's reliability depends on its constituent components and standards to which it was planned and designed. Introducing pseudo-measurements may introduce uncertainties due to possible operating and environmental conditions.

Being able to monitor voltage stability is a key part in preventing voltage collapses [6]. To avoid uncertainty of the network state estimation, remote points are added to a significant number of points on the $11kV$ distribution networks. However, there is a significant cost associated with the acquisition of such real-time measurements. Hence, careful choice of location from which measurements can be acquired is needed. If such measurements (or their approximation) may be accommodated using the existing smart grid infrastructure and technologies (e.g. the currently deployed smart meters), such expenses may be significantly reduced or avoided. Additionally, it is expected that such smart grid technologies may be utilized by a planner to more accurately determine weak points of a LV distribution system.

From the Quality of Service(QoS) perspective, one of the most important constraints on the distribution system design is the voltage level at the end-user (residential customer) point. Knowledge of the voltage deviations at different locations can indicate the strong and weak parts of the grid [7]. Current approaches address the several load points along the line, by using a series of calculations in order to estimate the voltage level at each load point. As smart metering technology has been proven to achieve better reliability (because of its real-time capability [8]), reliability can also be involved in predetermination of weak points in the grid. Identification of such points can point a system designer on important locations in expansion/reinforcing planning process.

Within the NOBEL project (www.ict-nobel.eu), we have developed a smart metering platform [9] that among other functionalities, specializes in near real-time acquisition of metering information from the grid as it is reported directly by the smart meters. A plethora of additional information apart from consumption meter readings are reported, including voltage, frequency, current, active power etc. Based on this information, as well as more advanced capabilities for direct interaction with the meters e.g. in order to increase the frequency of data reading, one can get a much finer view on the grid infrastructure that can complement the view offered by dedicated equipment.

Combining detailed information with analytics as well as geographic information system (GIS) tools, a better under-

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standing on potential problem areas can be obtained. Additionally, management decisions (e.g. maintenance operations) can be automatized in cooperation with the enterprise systems e.g. ERP. The main contributions depicted here are apart from investigating these directions, to also demonstrate an example case with real-data streaming in from 5000 meters currently deployed and communicating with the NOBEL smart metering platform and its services. The results shown can be considered as an intermediate step that could empower more general approaches such as network state estimation, and also in longer term pain points that have to do with grid reinforcement and grid planning.

II. Energy Distribution System Monitoring

A. The business need

The QoS, e.g. ensuring nominal voltage to the consumers, is a composite function of several variables such as voltage drops in the lines and transformers, tap settings in the transformers, voltage received at the source stations in the grid, etc. Additionally, the network constraints and ageing degrade the service quality and therefore require adequate expansion of the existing substations and/or feeders timely. Still, delivering an uninterrupted supply and high QoS is among the goals of every Distribution System Operator (DSO).

Electrical equipment are rated to operate within a specific range of voltage levels, deviations outside this operational range may result to malfunctions. Low QoS or even interruptions in the supply have been associated with harmful effects (and in many cases filings for financial compensation against the DSO have been undertaken) to the equipment of the supply authority or customers. To ensure the supplied voltage levels, the regulatory authorities have specified the limits for the deviations e.g. within the European Union the nominal voltage is regulated to 230V $\pm 6\%$ at 50Hz [10]. Having better assistance in minimizing or preventing violations in delivered QoS (one dimension of which is the nominal voltage), as well as enough planning for it is highly demanded.

Since finding the weak points within the grid is a highly complex process, that often involves sophisticated mathematical modelling and intensive numerical computation with large-scale data, there many uncertainties and inaccurate factors that come with it [11]. For that reason, the computer-based decision-making systems [12] have become an essential tool for the distribution expansion planning. However, lack of fine-grained network measurements, together with other network information constitute a limiting factor. Additionally, the distributed generation of energy we well as electric mobility approaches are challenging the limits of such computer-based estimations with their unpredictable nature. Provision of detailed measurements at low cost such as the one acquired by the smart meters may be of significant assistance.

In order to better understand network state, measurement placement techniques are used to improve state estimation. Some of the techniques [13] involve starting with already available measurements and trying to reduce the system's non-observability by adding a few pseudo-measurements. Other methods [14] try to design a perfect measurement system with the help of available abundant measurements. Applying such techniques can become unrealistic if applied to distribution systems. The following reasons were identified [5]: (i) abundant measurements do not exist at the distribution level, (ii) most of the techniques use a large number of P and Q flow measurements, which becomes expensive at the distribution level, (iii) observability cannot be overcome by the addition of a few pseudo-measurements.

Apart from avoiding potential malfunction on the grid, a DSO may also find such information of high importance for making decisions towards future grid expansions, or planned grid reinforcements. As the expansion affects the electricity load growth, which from some point onward will require grid network reinforcement, delivery of the same quality of electricity (e.g. without voltage drops) may be challenging. In fact, the majority LV network expansions arise from the new customer connections e.g. the provision of new supplies for a new housing. Without proper measurement in place such a process results in absorbing more investment than really needed at that given point [15].

Another aspect is that of the distribution system planning which deals with how to minimize new facility installation costs and operating costs under the constraints of [16]: (i) current capacity of line and transformer, (ii) voltage drop at each load point, (iii) demand-supply balance with respect to the power flow. Detecting and defining facilities to be installed and/or reinforced will ensure the overall system stability i.e. voltage and power quality are within standard ranges [17]. The cost-effective service quality is the main constraint of distribution system planning.

The installation of new measuring equipment and communication infrastructures represent a large investment. However, with the existing efforts towards large scale deployment of smart meters and their capabilities for measurement and communication, one can realise similar functions at a fraction of the additional cost. The smart meters may simply replace the devices required at sensing points whose large number is not possible for cost and logistic reasons, by reporting e.g. voltage and current measurements directly to a data acquisition system such as a smart metering platform. Since all the meters have to communicate with such systems, it is not expected to be an overhead the transmission of additional system data to that (or other) system(s). Having visibility in the whole grid (up to residential endpoint) using real measurements instead of simulation based (mostly static) estimations may provide the key to better decision making and hence bring business advantages.

B. The NOBEL monitoring approach

The NOBEL project has designed an energy service platform [9] mostly focusing on acquiring the data, processing it and providing value-added services to its stakeholders. A key service is the "monitoring" service, which is responsible for the collection of data from the smart meters and concentrators in a pull, or event-based, mode. Apart from the traditional information needed in the typical smart metering cases e.g. energy consumption or production, we also take advantage of all smart meter sensors and transmit additional information of each metering point e.g. voltage, frequency, current, active power etc.

Figure 1. Smart Grid Neighbourhood – DSO management application

One of the main motivations for developing the platform was to decouple the energy applications from the data acquisition and management, and hence being able to rapidly develop lightweight end-user applications targeting all smart grid stakeholders including residential end-users and the DSO. Such an application developed is depicted in Figure 1. This is a web application (named NOEM) that is also mobile device friendly, and hence can be accessed via a web browser from anywhere. Part of the functionality of interest to this work are the monitoring and management activities that the operator can perform.

```
/*
 * Sent from a concentrator/smart meter to the Energy Service Platform
 * This encapsulates a measurement of various electricity metrics
 */

option java_outer_classname = "NobelPowerMeasurement";
option java_multiple_files = true;

package eu.ict_nobel.gpb.meter.energy;

message PowerMeasurement {
    required double voltage = 1; // the voltage in Volts
    required double current = 2; // the current in amps
    required double activePower = 3; // the active power in kW
    required double reactivePower = 4; // the reactive power in kvar
    required double powerFactor = 5; // the power factor - dimensionless
    required double frequency = 6; // the voltage frequency in Hz
}

message PowerMeasurementList {
    repeated PowerMeasurement measurements = 1;
}
```

Listing 1. Electricity Monitoring – Google Protocol Buffer Definition

In late 2011 the first trial of the NOBEL project took place, while since mid-summer 2012 the second phase is in progress. This means that the developed platform is used for monitoring and management of the approx. 5000 smart meters that connect and communicate meter readings and additional information. Among the additional information is also the voltage as measured by the smart meter, and communicated in the form depicted Listing 1. All acquired data, after some sanity checks, is stored in the “cloud” and made available via the services of the platform. The developed services [9] are results of complex queries and assessment done transparently on the data and customized for business purposes.

Additionally the users of these approx. 5000 smart meters have access to the platform and can see their consumption (resolution of 15 minutes) as well as their energy prediction. A smaller fraction of them can perform more advanced tasks that are out of the scope of this work such as energy trading i.e. buying and selling energy in a marketplace using the brokering services of the platform. With all the data streaming into the system (coming from the approx. 5000 distributed sensing devices i.e. the smart meters) we are able to do fine-grained analytics and acquire a timely and highly detailed visibility on the grid itself and its stakeholders.

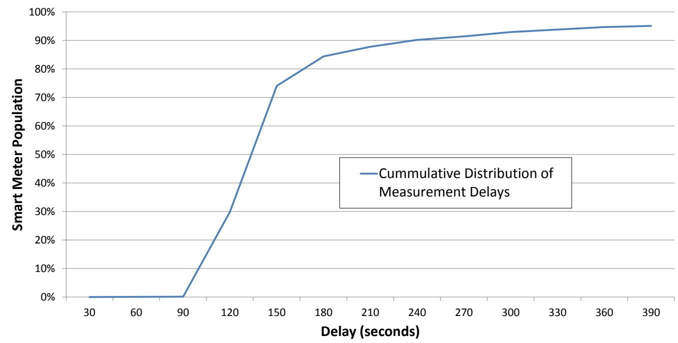

Figure 2. Cumulative distribution function for measurement delays

For performance reasons, selected technologies and methods have been adopted [9]. The measurements may be communicated in bulk in order to enhance performance and scalability of the system [18]. Considering the large number of meters, Figure 2 shows the cumulative distribution function for delays in the measurement data from the moment that it was generated by the smart meter, up to the final stage that it was collected by the energy service platform. This basically shows how long one can expect to wait for a particular percentage of device measurements from the network. For instance, one could expect to have around 90% of the measurements within $240 seconds$. The realistic communication assessment (without any effort to optimize it on the DSO side), is especially interesting for the consumers of the data e.g. the state estimation algorithms, as it can give an indication of how long one would have to wait in order to have enough measurements to start the calculations.

III. Experimental Assessment and Discussion

Although within the NOBEL trial every smart meter reading received contains many electrical measurements, as shown in Listing 1, here we will only focus on the voltage deviations as proof of concept for the information that can be acquired and assessed. In particular the voltage drops are a well know issue [7], and by using the data collected from a large number of distributed voltage sensors we were able to identify weak areas (where low voltage is detected) in the grid.

As the NOBEL trial occurs within the European Union, the nominal voltage of 230V $\pm 6\%$ at 50Hz [10] is used as the point of reference. In practice, this means that received voltage deviations at consumer’s premise may deviate in the range of 216.2V – 243.8V. With application of the European standard EN 50160 [19] where voltage characteristics at the customer’s supply terminals under normal operation conditions are specified, the range of variation of the 10 minute RMS of the supply voltage is $\pm 10\%$ for 95% of a week. In other words, for more than 8 hours a week no boundaries are applied to the received voltage. By analysing the real smart meter data of the trial we identified many meters exceeding the regulatory boundaries of 230V $\pm 6\%$.

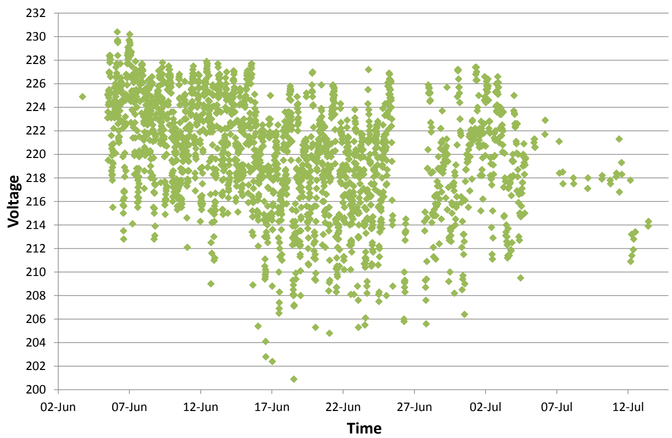

Figure 3. Example of a device violating the lower voltage boundary

Figure 3 shows one of the smart meters reporting values that cross the lower boundary of the regulation ($leq216.2V$). The depicted measurements over the period of more than a month (for this smart meter) contain 3244 voltage measurements in total, being taken at different points in time (having minimum 15 minutes sampling rate). Out of these 3244 measurements, 695 measurements were identified as dropping under the lower voltage limit. Although the average voltage reported by this smart meter is 219.7V, 21.42% of the measurements had voltage values below the allowed deviation zone. Some voltage measurements even were reaching values near the 200V (a 13% deviation).

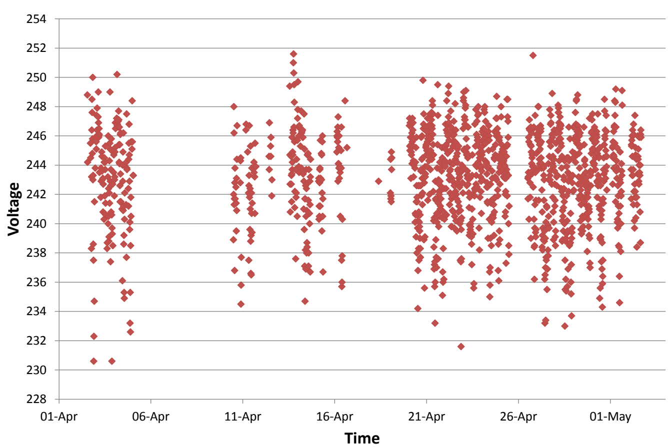

Figure 4. Example of a device violating the higher voltage boundary

Similarly to the deviations for the lower boundaries excess, many measurements were detected crossing higher voltage boundary ($\geq 243.8V$). As shown in Figure 4, the violation rate is much higher than on the Figure 3. The data covers again a period of more than a month, and the set contains 1355 measurements in total. Out of these 1355, 617 measurements were identified going over the higher voltage limit ($\geq 243.8V$), which results in 45.54% of the measurements outside the allowed deviation zone.

These two example meters show that with greater resolution on measurements new insights may be obtained. The entire set of the trial had 4470 smart meters being distributed within entire electrical infrastructure. Although the data set contains a large number of sensing points, the data for each smart meter is not available over entire spectrum (due to experimentations in connectivity, platform development etc.). Nevertheless, existent measurements were enough to produce the voltage statistics for many devices in distinctive timeframes. Figure 5 depicts statistics for smart meters measuring voltages beyond the lower voltage regulation. The 25 shown devices were selected for having more than 1% of measurements outside the 230V $\pm 6\%$. They are sorted in function of the percentage of the measurements being outside the voltage deviation limits. The figure also depicts the averaged voltage for each of the smart meters, which seems to correlate with the measurements percentage curve.

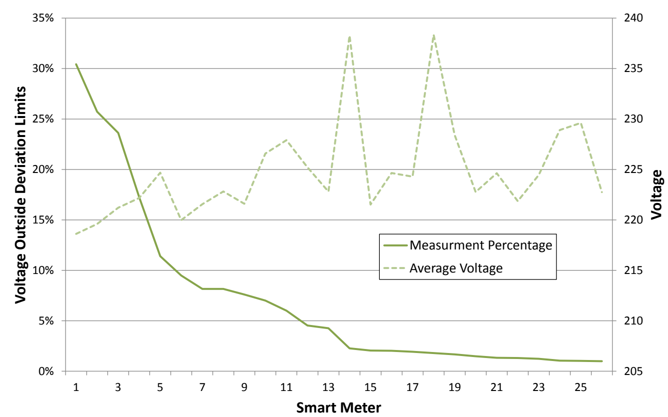

Figure 5. Measurements with voltages outside lower deviation limit

Interestingly, the first 5 devices were being identified as having more then 10% of measurements outside the $\pm 6\%$ boundaries. If smart meters are not malfunctioning, then the limits set by EN 60038 [10] are probably being violated. Although, remaining points do not seems to violate the specifications of the standard EN 50160, these points should be considered as possible weak points of the network. In any case, the result is that the functionality of the 5 devices should be checked for potential malfunctioning in the next maintenance opportunity, or grid reinforcement should be considered. In the latter case, one has also to carefully consider the identified point in the electricity infrastructure for any future grid expansion planing.

Figure 6 depicts the same as the Figure 5, but for higher voltage boundaries ($\geq 243.8V$). Sorting is done from the most misbehaving devices to the least ones. In contrast to the previous case, here we had more then 120 smart meters having at least 1% of measurements over the allowed deviation limit. Similarly to the previous case, it seems that both curves, measurement percentage and average voltage, are correlated. We can observe that more than 30 devices are having average voltage outside the limit. Also ≈ 80 smart meters violate the

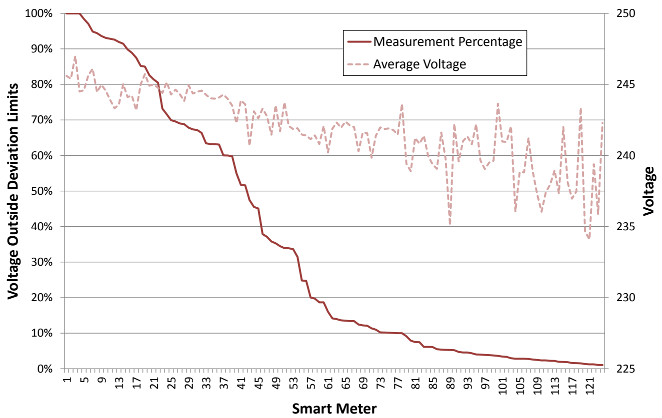

Figure 6. Measurements with voltages outside higher deviation limit

maximum voltage tolerance for more than 10% of the time.

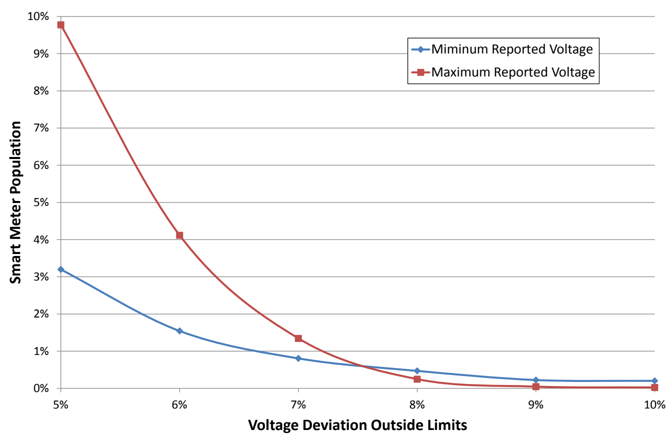

Figure 7. Device distribution near to and exceeding deviation limits

Since many critical areas were identified, we expended the analysis to identifying actual percentage of all devices crossing boundaries of voltage tolerance. Figure 7 depicts a more general view on the infrastructure as it compares on number of all the smart meters involved in the trial. The figure depicts percentage of those smart meters having at least one measurements in excess of the nominal voltage values (both for higher tolerance and lower tolerance crossing).

As we can witness, for instance 4.12% of the meters report voltages that go above the 6% (≥243.8V) of the threshold. This number declines significantly, as below 1% of the meters report values above the 8% ($\geq 248.4V$) or 9%. As it can also be seen, the majority of the meters ($\approx 90\%$) are reporting values $\leq 5\%$ of voltage deviation ($\leq 241.5V$), while a smaller fraction of them is near the upper limit between $5\% - 6\%$. Similarly, we can see that voltage drops beyond the 6% deviation ($\leq 216.2V$) are reported only by 1.54% of the meters. Again the population significantly declines and under 1% of the meters report voltage drops under 7% deviation ($\leq 213.9V$). The majority of the meters (over 97%) are reporting voltage values $\leq 5\%$ of voltage deviation (≥ 218.5) and a fraction of them is near the lower limit between $5\% - 6\%$.

As already argued, having a large number of distributed sensing points within the smart grid may provide a much better visibility to its operations. Although today none of the commercially available residential smart meters can replace high-precision dedicated equipment e.g. network analysers, it may provide good enough information at a fraction of the cost over an existing infrastructure (already deployed for smart metering). One obvious drawback is the communication delay, as shown in Figure 2, which may be too high for reacting to critical grid events. Hence we do not consider that this approach is viable for real-time critical events, but nevertheless may provide good quality of information and in a timely manner so that new insights in the infrastructure can be obtained.

IV. Conclusion

Within the NOBEL project an energy services platform has been developed, which we also use in order to collect and analyse additional technical parameters such as voltage. Our data is coming from approx. 5000 real smart meters connected to the platform and delivering among other measurements the current voltage at the residential user's endpoint. Based on the analysis, we can identify voltage deviations that exceed the nominal voltage value which in the European Union is agreed to 230V ±6% at 50Hz [10]. Such excess is either on the upper end (over 243.8V) or on the lower end (below 216.2V), and as the data show exist under normal operative conditions. These (especially the ones exceeding the lowest voltage allowed deviation) are the weak points in the network which may prohibit further network expansion. Such repetitive behaviour may indicate problem zones in the DSO system which will need to be closely looked upon.

The next steps would include automatic recognition of such event patterns as well as putting them into context e.g. within a building or a street. Additionally inter-dependencies will need to be identified and analysed e.g. correlating voltage drops with malfunctions, faulty wiring etc. as these may result to safety hazards. The depicted efforts have shown that with proper analysis new insights on the operation of the grid can be obtained, and that these may be used as an intermediate step to empower other grid related processes.

Significant work within the grid is devoted towards maintaining its stability as well as QoS. Auxiliary processes such as grid estimation, grid reinforcement and grid planning are mainly based on data coming from selected metering points or are computationally estimated. Smart metering coupled with high-performance communication can provide possibility to raise awareness for event-driven real-time events, like load congestion, system stability, equipment health, outages and demand response events. A fully functional assessment and decision-making system [3] can then employ management decisions and adjust its behaviour. Having real-sensed values, instead of estimated ones, may allow DSOs to actively control their network and improve their QoS. Even new approaches may be realized in scenarios where e.g. the end-user connects devices in the network that may lead to voltage drop and hence is notified by his provider for potential malfunctions or safety issues. Such value added services may provide new business opportunities in the smart grid era.

V. ACKNOWLEDGEMENT

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VII. BIOGRAPHIES

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Stamatis Karnouskos works at SAP Research investigating the added-value of integrating networked embedded devices in enterprise systems. For the last 15 years, he has led efforts in several European Commission and industry-funded projects related to smart grids, Internet-based services and architectures, software agents, mobile commerce, security, and mobility. He is actively involved in several consultations at the European Commission as well as at a national level, dealing with System of Systems, Internet of Things, Energy Efficiency, and SmartGrids.

Per Goncalves Da Silva joined SAP Research in April 2010 as a PhD candidate in the area of Future Energy. Before joining EU NOBEL, he has participated in the EU SmartHouse/SmartGrid project. Prior to joining SAP, he worked as a Java software developer for the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. He holds a Bachelor of Computer Science (Hons) from Monash University.