Using a 6LoWPAN Smart Meter Mesh Network for Event-Driven Monitoring of Power Quality

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Abstract—**Power quality monitoring is one of the key issues of managing an electrical grid, which is becoming even more important with more distributed and more variable generation. Today expensive equipment allows monitoring of the power network at key points, but for cost reasons this can not reach the residential end-user. To prevent an excessive need for specialized monitoring hardware, e.g. network analysers, it is proposed to engage the capabilities of modern smart meters which can monitor and report power quality events (e.g. voltage deviations). Subsequently a grid operator can follow up with actions in an affected area in order to analyse problems e.g. by increasing the sampling rate. Although the smart meter precision is not comparable to the precision of a commercial network analyser, in large numbers distributed smart meters forming a mesh network can provide sufficient information for power quality in an area while keeping the monitoring overhead and the cost low. It is shown that by using modern interoperable wireless communication protocols and Internet services, the proposed system has a high degree of flexibility, and good potential for scalability and resilience. The preliminary evaluation shows that the smart metering infrastructure, if coupled with suitable information and communication tools, can offer innovative value-added services and enhance existing business processes.**

I. MOTIVATION

The smart grid [1] has emerged in the last years as a promising area of research and evaluation. Hence hundreds of projects are conducted worldwide investigating different aspects of it, ranging from futuristic academic concepts to short-term deployable functionality and associated business models. The promise of the smart grid is to provide the next-generation electricity network that will feature advanced configurability, reactiveness, and self-management. The vision of a complex collaborative infrastructure is based on information and communication technologies enabling near real-time monitoring, assessment and management. These goals are challenging since the grid will be composed of consumers that also act as producers (hence prosumers) that will be largely distributed.

As in any emergent infrastructure, the search for viable business models is not clear at its beginning. In the smart grid there are several ideas of what could be offered in terms of technology, but strong cases for their business benefits still need to be proven in practice. The smart grid era promises to empower business processes with new capabilities to tackle problems more efficiently. One key capability is to provide meter readings with a higher frequency and lower latency compared to the traditional infrastructures, where in the past readings have been gathered with larger intervals, e.g. monthly. This new granularity (e.g. 15 min or less) could offer insights for both utilities and their customers. Due to the higher granularity and flow of information, stakeholders will be able to closely examine the grid state and its services, as well as the effect their actions might have on it.

The task of supplying power from the distribution substation to end-users is carried out by Distribution System Operators (DSOs), who need to ensure high quality of service. Power quality can be described as a set of parameter values, such as continuity of service, variation in voltage magnitude, transient voltages and currents, harmonic content in the waveforms etc. [2] Deviations in power quality can lead to outages, malfunction and even damage of electric devices. Through fine-grained monitoring one can assess quality of service parameters that are directly linked to user-satisfaction. Today, grid operators mostly rely on multi-sensor systems named Phasor Measurement Units (PMU) that are placed on points of interest in the grid, in order to monitor QoS. Some have enough intelligence to automatically respond to QoS events within the network. Eventually, these could provide the emerging smart grid with the desired features of self-healing for detected anomalies. To do so, one would have to create a network of PMUs and Phasor Data Concentrators (PDC) to collect the information and transmit it to a Supervisory Control And Data Acquisition (SCADA) system at control centres. As an example the FNET project [3] utilizes a network of approximately 80 high-precision Frequency Disturbance Recorders to collect syncrophasor data from the U.S. power grid [4]. The monitoring information can be correlated with other context-specific information such as location or asset specific data to help technicians diagnose and correct problems in the grid.

Today such power quality systems are costly and are operated by the DSOs. However, with new capabilities in the smart grid, as well as rapid advancement of modern Internet technologies at application and protocol level, complementary solutions become possible. The usage of Smart Meters for voltage monitoring has been investigated [5] and shown to be feasible approach, although the power line communication technology used puts severe constraints on the bandwidth. However, if such measurements may be provided along with the smart metering data, then analytics may provide a good insight on the infrastructure [6].

This paper investigates the potential combination of the modern smart meter sensory devices and application logic over an event-driven Internet infrastructure using wireless low power technologies. The focus is explicitly on a promising set of emerging technologies, i.e. IPv6 and more specifically 6LoWPAN (defined in RFC4944), REST and a publish/subscribe model, to assess the feasibility and potential benefits of such solutions. The main technological motivators are heterogeneity, openness, scalability and agility.

II. BUSINESS CASE: POWER QUALITY MONITORING

A. *Business Case Analysis*

Power quality is usually monitored at a very fine-grained level with task-specific embedded devices, such as PMUs or network analyzers. Although there is a need for higher degree of real-time monitoring and analysis, costs are prohibitive and still remain a limiting factor. A pervasive deployment of these devices is not economically viable, and, therefore, they are shared among multiple customers. Deviations from acceptable quality levels can cause blackouts, or damage equipment leading to financial impact for stakeholders. If the retailer cannot guarantee the legally required or contractually guaranteed quality of supply, this may impact customer loyalty and lead to financial losses. Hence improved power quality monitoring where all stakeholders could access power quality information and consider it for further decision making is a promising business case.

As voltage may vary significantly in distribution networks, this has an impact on the energy efficiency side [7]. Overvoltage can result in a reduction of equipment lifetime and increased energy consumption without any performance improvements. Transients, i.e. large and brief voltage increases, can destroy electronics and degrade equipment parts. Phase voltage imbalance, e.g. for 3-phase electrical industrial devices, may also lead to heating and wasting of energy [8].

The monitoring challenge can be tackled via extensive use of monitoring devices embedded in the grid, such as fine-grained level network analysers. However, their cost is still a limiting deployment factor. Therefore, hundreds of customers are usually monitored by a single network analyser, which limits their ability to pinpoint the exact location of potential problems. In this setup, a DSO could only monitor a branch of its distribution network, without access to enough fine-grained information to capture QoS issues on a specific end-point.

The complexity of the electrical grid is growing and with the introduction of highly distributed energy generation as well as volatile consumption (e.g. via electric car charging), maintaining power quality is an increasingly challenging task. This implies not only investment in the infrastructure hardware as such, but also in the monitoring of it, as well as in the means to quickly react to potential quality deviations via real-time decision support tools and management. With respect to electrical wiring, national electrical guidelines may set requirements for maximum voltage drop allowed in a circuit conductors. This ensures reasonable efficiency of distribution and proper operation of electrical equipment.

This work investigates how a smart meter mesh network is capable of monitoring and triggering an event in case the maximum voltage deviation threshold is exceeded. In this way, distribution grid problems can be detected early (preventive maintenance), and corrective actions can be planned and realised on-time, ideally before bigger problems occur. Once a smart meter identifies that the quality of supply (e.g. voltage) is close to, or crossing, the boundaries of acceptable deviation, an alarm event is raised and sent to the monitoring application. If the issue occurs frequently on one or more end-points, an investigation should then be considered by the DSO. This could also be an indicator for the end-users that they have connected malfunctioning devices in the grid, which should be unplugged.

After receiving an alarm event, an operator should be capable of identifying if intervention is needed. Therefore, metering data of higher precision and frequency should be available to the operator. Using the capabilities of the smart meter mesh network considered in this work, operators should be capable of increasing the sampling rate of metering data dynamically and on-demand. Sampling voltage in $10sec$ intervals should be sufficient for diagnosing a wide range of cases involving voltage deviations [5] [6]. Once the sampling rate is increased on one or multiple meters, data is transmitted to an enterprise system. Here, the frequency data is monitored and analysed in near-real time e.g. correlated to failure simulation models etc. Grouping small sets of meters and analysing them in conjunction could also be considered. For instance, grouping multiple meters in a building into one single virtual meter. If this group issues an event, an operator can require higher sampling rate for the entire building to help diagnose issues within the building.

Two exemplary processes for grid reinforcement within the capabilities of the proposed smart meter mesh infrastructure may be realised. The first process seeks to monitor the grid for reinforcements as it naturally expands, since it is expected that this will lead to a point where some nodes will start issuing QoS events, e.g. voltage issues [6]. The second process consists of the determination of stategically important points in the grid when the operator deems necessary reinforcement or expansions. Monitoring with higher frequency of points of interest in the grid may provide better understanding towards the selection of the best strategic point for reinforcing the grid. As the cost of grid extensions or grid reinforcements can be very high for the DSO, better understanding of what is happening on the end-points and the associated impact may be of key importance for planning and optimizing strategic investments.

The example scenario depicted in this work is a natural extension and usage of the capabilities of advanced meters available to the market [9] in conjunction with modern communication infrastructure and web services. As electricity providers are reluctant to make new infrastructure investments, the business benefits that can be achieved with the new technology must be clearly shown.

B. Expected Business Benefits

By realizing an infrastructure as we have discussed, several business benefits could be potentially achieved. Indicatively we mention:

- The DSO can have a proof of power quality delivered to the residential user. This enables the DSO and others, e.g. energy providers to be able to prove to the user that high quality electricity was delivered and that could contribute positively to the provider's reputation, which may bring new clientèle or increase customer loyalty.
- The residential customer can monitor his own power quality and even do potential on-site immediate diagnostics for misbehaving electrical appliances that he may plug in his premises.
- The customer can make additional comparisons of energy providers not only based on price but also on the quality of electricity offered, and select his future contract in a much more conscious way. This may increase the competition among providers for high quality energy offerings.
- Power quality monitoring could be coupled with other envisioned smart grid services, e.g. device identification and better analytics, to better predict the potential effects of specific devices on network stability and improve early problem identification and preventive maintenance.
- The DSO can use the information acquired in order to optimize the voltage delivered, i.e. apply conservation voltage reduction (CVR) and volt/VAR optimization [10] which may lead to reduction of energy up to 4% [11].

An interesting question that is raised is to what degree these business requirements e.g. of residential customer power quality monitoring, with low-cost capabilities, can be satisfied, especially when taking into consideration the future smart meters deployed that are expected to be able to provide fine-grained data in high frequency metering. If sensor-wise the smart meters can deliver similar information both in quality and quantity, one may realise a "cheap" alternative for a specific subset of functionalities. To do so, the following actions are envisioned:

- Equip the smart meters with sensors that are able to monitor the parameters needed for power quality monitoring in a fine grained form. To some extend this functionality is already built-in today. However, there are significant differences with respect to the monitoring intervals and their on-meter storage.
- Enhance the smart meters with modern communication capabilities so that they can communicate (e.g. over IP) on-demand the necessary data. The data itself should be in a standardized format so that other entities can operate on them (aggregate them, process them in the network etc.). Additionally the existence of multiple alternative communication paths could enable information extraction and interaction during critical situations.
- Allow on-device customizable logic execution on the smart meters, so that external entities can configure or even program them with task specific logic. For instance it should be possible to increase the frequency of measurements on the power quality monitoring factors, set thresholds for them or even execute application logic on the meter for pre-processing of these factors.
- Provide an infrastructure where the smart meters and in-network services can interact in an open and standardized way. The infrastructure should enable collaboration and interaction for building up large scale systems. Hence issues like scalability, lightweight communication, event-driven interaction, on-device and in-network processing are of interest.
- Support the integration and interaction with enterprise systems so that business processes take advantage of the infrastructure itself and changes to the enterprise level can easily lead to adjustments on the network and the smart meters to support the changes in business requirements.

III. ARCHITECTURE

The metering infrastructure is composed of smart meters in a mesh network and, optionally, concentrators. A smart meter measures the amount of energy consumed or produced by a customer and submits periodic readings of the amount produced or consumed. It may also be able to measure and report other important measurements such as power, frequency, voltage and power factor. Furthermore, it can issue events, such as for a change in state, e.g. on or off, and when a threshold is violated, such as a customer drawing more power than his contract allows.

The developed multi-layered architecture is depicted in FMC notation (www.fmc-modeling.org) in Figure 1. Several layers exist i.e. the device layer, the middleware and the enterprise services and applications. Embedded devices (in our case smart meters, concentrators etc.) are composed from a hardware as well as a software part that enables their low level programmability. On the top layer we have various (enterprise) services (here abbreviated IEM) and applications that can form mash-ups (e.g. energy management system, energy portal etc.). Between the two, there is a middleware layer partially at infrastructure level and partially at device level (in our case the DCP).

The Enterprise Integration and Energy Management System (IEM) is an enterprise service platform providing energy service that can be easily integrated over the web in other applications [12]. In essence, it is a collection of REST (Representational State Transfer) services which can be used to manage smart metering infrastructure, e.g. smart meters and concentrators, and its users. It interacts with the underlying smart metering infrastructure so that it may be configured, and it acquires, processes and stores the metering information. Aside from the data capture, monitoring and management services, the IEM also provides forecasting services and energy optimization services. The forecasting services give a new horizon forecast of the energy production or consumption of a device. The optimization services are there to interact with larger scale customers, such as a factory, or a supermarket,

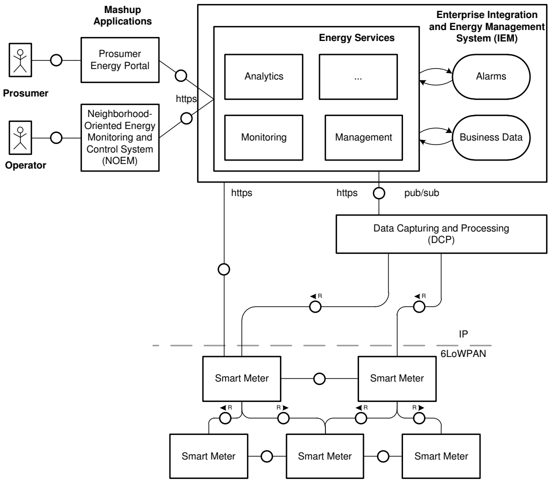

Figure 1. Architecture Overview

to enable demand response scenarios. In this case, if the IEM detects a potential balancing problem, it can contact larger consumers and negotiate [13] an appropriate response, either an increase or decrease of consumption.

The Neighbourhood Oriented Energy Management System (NOEM) is a management and monitoring application built on top of the IEM platform. It enables grid operators to monitor the state of the grid by presenting current and historical data as supplied by the smart meters e.g. energy and power usage, measures e.g. voltage and frequency, and any events generated by the meters e.g. the violation of a power threshold. It also gives grid operators direct access to the smart meters allowing them to configure parameters e.g. metering frequency, and control the state of the meter e.g. interrupt the supply of energy to the customer. It also enables operators to create groups of meters, so they can be monitored as a single ‘virtual’ entity. In this case, the consumption and production of each meter in the group is aggregated. This grouping functionality allows for a more flexible view of the grid, where whole areas and sub-areas can be monitored separately.

It is expected that future smart meters will support IP connectivity directly and will be able to report their measurements directly to a metering platform using open Internet technologies. To tackle heterogeneity, the architecture is also able to deal with smart meters that communicate with proprietary protocols through concentrators that connects to the smart meter network transparently for the IEM. Each smart meter hosts a developed communication and hardware adaptation platform (IPC) that allows end-to-end connectivity in the entire network. Given by the resource constraints, Contiki, an efficient OS for embedded objects is chosen as the operating system for the meters. The focus here is on next generation IPv6 enabled smart meters i.e. meters that communicate using the IETF-standard “RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks” (defined in RFC6550) over 6LoWPAN which enables also resource constrained wireless devices to communicate using IPv6.

The IPC is integrated in each smart meter and provides a naming service which ensures the smart meters will get a globally unique IPv6 address when they connect to the smart meter network. By using the newly standardized routing protocol for low-power wireless networks, RPL, the smart meters will automatically configure their routing tables. This makes it easy to add new meters without manual network reconfiguration. IPC also provides standard UDP and TCP communication to be used by DCP. By only using a subset of well connected smart meters as gateways to the rest of the Internet (mesh network), less infrastructure support and dedicated hardware is needed. Depending on the available infrastructure, the gateway smart meters could be connected either directly to an Ethernet, or over a GPRS/3G modem. The combination of IPv6 addresses and standard communication protocols enables direct smart meter communication, where the higher level services can target a specific meter with requests.

The motivation on using wireless communication is due to the fact that it enables shorter reading intervals compared with standard power line technologies. While high bandwidth power line data transfer can be achieved, the cost is much higher compared with the low capacity infrastructure present in existing power grids. Existing low cost power line communication can be appropriate if the readings are reported at 15 minute intervals or longer, which has been more than enough when the meter readings only are used for billing and not for real-time network monitoring. More frequent polling for data would cause the system to show unreliable behaviour.

Although meters can directly report their measurements to the enterprise system, it makes sense to have in-network Data Collection and Processing to abstract network details from the IEM. DCP captures information from both IP-connected meters and meters connected via proprietary protocols with a concentrator. The middleware follows the publish/subscribe paradigm that enables efficient gathering and in-network processing of information and fosters the implementation of loosely-coupled fully distributed systems. The business services express their information needs, e.g. getting meter readings with a certain frequency for a selection of smart meters. The middleware is responsible for adaptively using the network to efficiently fulfil them.

For resource constrained smart meters communicating in low power networks via 6LoWPAN, DCP tightly integrates with IPC to efficiently use the available resources. The 6LoWPAN address compression makes it possible for devices sharing the same address prefix to send meter readings in single 802.15.4-packets without need for fragmentation.

IV. EXPERIMENTAL RESULTS

The main goals of the carried out experiments focus on the aspect of evaluating a subset of communication aspects of the 6LoWPAN mesh smart meter network and its interaction with the energy services, i.e. the delay between issuing a subscription, e.g. due to an alarm raised in the grid, and the reception of data from the smart meters. By doing so it is possible to evaluate if such actions for monitoring can be done in an acceptable time-frame for the operators to capture the grid events.

A set of five real wireless sensor nodes form our testbed, where one node acts as the gateway, hence enabling the rest of the nodes to connect to the Internet and thereby to the DCP. The nodes automatically form and maintain a routing tree based on the RPL standard, with the gateway node responsible for connecting the sub-network with the Internet (as defined in RFC6550). To create a more realistic scenario, the nodes are manually configured to force the routing tree to contain at least two hops, with three of the nodes at two hops from the sink.

Due to their similarity to future smart meters equipped with low power communication technologies, we chose the sensor node platform WiSMote as the basis for the experiments. These nodes are equipped with MSP430F543 microcontrollers (which is a modern version of the microcontroller used for the well known Tmote Sky platform); 16 kB of RAM; 256 kB of program memory; 2 MB of external flash; a 802.15.4 radio and the possibility to connect up to eight external sensors.

Operationally, the IEM issues subscription requests which are disseminated by DCP and IPC to the targeted nodes. Once a metering point, or a group of them, is specified through a subscription, data is captured and processed by the DCP middleware on the individual node and the network. In the experimental setup, the data used on the individual nodes is a list of pre-recorded metering readings (hence simulating a realistic scenario).

The meter triggers an event whenever a particular measure violates pre-configured thresholds. The event is processed by the enterprise system, and a decision is made on whether the frequency should be increased or not. This approach safe-guards the network from being flooded in case of a wider problem, given that bandwidth in the current systems is limited.

The nodes send the meter readings with the dynamically adjustable frequency, which was specified by the subscriptions. The data is pushed to the IEM via REST web services dedicated for acquiring metering data [12]. All readings (including their timestamp) are stored together with the reception time by the IEM monitoring service. With this information, the delays to make or change subscriptions and the message loss ratios can be determined.

As for on-demand power quality monitoring of the grid a high frequency and quick response time are necessary, the DCP is configured to start publishing this data as soon as a subscription arrives. For the evaluation an Internet connected IPv6 distributed testbed was used i.e. the IEM services are hosted in Walldorf, Germany, while the mini-testbed and the DCP root instance are running in Stockholm, Sweden.

An iteration of the data collecting experiment used to validate the design consists of the following process (which in the experiment is repeated 80 times):

- *Step 1:* The IEM issues a $60sec$ interval subscription for all meters. The time until all meters are reporting data is measured.
- *Step 2:* After $5min$, one of the nodes is chosen, in a round-robin fashion, as the target to increase its sampling rate to $10sec$. Again the time until the chosen node is reporting data with the selected (higher) frequency is measured.
- *Step 3:* All subscriptions are removed.

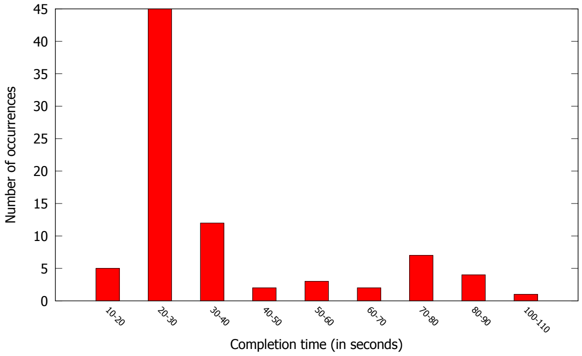

Figure 2. Histogram of the time it takes for all meters to report data after a new subscription

Figure 2 shows a histogram with the distribution of completion times for making a new subscription to all meters, and having received new data from every node. The histogram shows that in the majority of the tests all the meters responded within a $30sec$ period, with a tail of cases with higher delays. The higher delays, especially the little peaks at $70-90sec$, stem from cases where the subscription request for one meter was lost in the radio network. Since DCP uses periodic beacon messages both for discovery and information about the state of the nodes including the currently known subscription, it takes some time for DCP to become aware of the message loss and reissue the subscription. This time is configurable and set to $60sec$ for the test. Therefore, the DCP subscriber might need up to $60sec$ (or even more if the beacon messages are lost) to realize a request was lost, the re-send is subsequently delayed. This is a deliberate trade-off; technically a smaller refresh interval can be chosen, but at the cost of increased administrative messaging overhead.

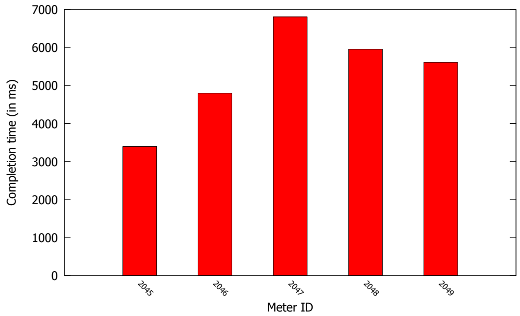

Figure 3. Average delay to complete a new subscription for a specific meter

A longer delay while subscribing to a group of meters can be accepted, as this is done occasionally and usually without specific timing constraints. For an individual subscription a shorter delay is desirable, especially if the subscription is made to investigate a potential grid problem. Figure 3 shows the average completion times for making an additional high-frequency subscription (interval $10sec$) for a specific node in the testbed. The delays in the graph reflect the network topology. The sink node shows the lowest delays, followed by the node one hop from the sink. For the nodes further away from the sink, the likelihood of packet loss when sending out the subscription request is higher, resulting in longer average initial delays, around $6 - 7sec$.

V. DISCUSSION AND FUTURE DIRECTIONS

The initial experimental results indicate that the system could be suitable for the business cases we have discussed. While the system does not provide the same timely performance as dedicated network analysers, it does allow for a steady flow of fine-grained measurements ($10sec$) at the consumption point. This spatially localized and pervasive data collection, complemented with real-time data collected at key points in the grid, could be used to pinpoint the exact location and nature of power quality issues experienced by end-users. Furthermore, it can also be used to assure end-users that the required power quality is being delivered, in cases of equipment damage or malfunction. While the evaluated granularity is not comparable to dedicated network analysers, it is a great improvement on standard $15min$ intervals. The technical evaluation shows that the approach is viable with existing hardware components, that could be used in next generation grid infrastructure.

In the current model the decision to increase the meter reading frequency is taken centrally, to avoid flooding the network. However, it may lead to some information loss, given that there is a short time period between an event being triggered, and the meter reading frequency being increased. To some extent this could be alleviated by suppressing spatially and temporally related alarms and information, which however, would lead to decreased amount of detail in the information about the grid. Finding an optimal balance between the infrastructure investments needed to minimize the lag between events and increased reporting frequency, and the usefulness of the monitoring service is an area for investigation.

VI. CONCLUSIONS

Internet technologies are increasingly penetrating traditional slowly evolving domains such as that of energy. The IT-empowered smart grid is expected to increase the speed of change. Once the envisioned capabilities are realized and offered in an open interoperable fashion, other value added services may include them in their logic or use it as part of larger scale analysis that may not be thought up to now. The focus of this work is on taking advantage of modern Internet-based communication technologies and services to realise new or enhance existing functionality. An aspect of the approach has been demonstrated by using the power quality monitoring; however the design is general enough so that it is applicable with minor modifications to other relevant areas including gas and water monitoring, where electricity is not available or not an option. The same holds true even for the electricity network in case of malfunctions; for instance in case of a black-out, battery powered smart meters connected in a mesh network, could try to convey their latest power quality measurements (which would not be possible to transmit due to power loss) and hence provide a higher quality of information prior to and during the incident. Although several issues still need to be tackled, this work proves that Internet related technologies and concepts can be successfully applied with the envisioned modern smart meters to provide business advantages for all stakeholders.

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