SUNSEED

Sustainable and robust networking for smart electricity distribution

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1 An executive summary

The FP 7 project SUNSEED proposes an evolutionary approach to the utilisation of already present communication networks from both energy and telecom operators. These can be suitably connected to form a converged communication infrastructure for future smart energy grids offering open services. The project objectives were achieved by valuable contributions of consortium led by telecommunication operator and comprising nine partners.

The technical part of the project was divided among five work packages, of which WP2 was dealing with the systems concept and business techno-economic analysis, WP3 was dealing with communication networking components and infrastructure of DEG smart grid, including the advanced measurement and control sensor nodes development, WP4 was dealing with integrated control, management and analytics, with particular focus to three phase distribution system state estimation and forecasting, and WP5 was dealing with field trial integration and validation, where the key technologies were tested and evaluated.

After more than three years the SUNSEED project achieved the following key outputs:

- 1st of a kind: Embedded secure element to secure WAMS credentials, integration within smart grid infrastructure (smart meter, DEG, WAMS), agnostic to underlying networking infrastructure.
  - Significantly improved security (level of electronic banking)
- Cellular networks, 4G LTE enhanced random access procedure (RACH): estimation and serving phases.
  - More simultaneously active devices per cellular sector
- Prototype of a phasor measurement unit fulfilling the distribution system operator requirements
  - For experimentation in different operating conditions with user-selectable capabilities with embedded secure element
- Prototype of a power quality meter with control capabilities
  - Running FPAI client with a load control via internal switches (on/off) or MODBUS interface
- An Efficient Consumption Optimisation for Dense Neighbourhood Area Demand Management.
  - Near optimal result with low computational effort and ICT overhead.
- Multiple networks single view integration
  - Power grid, Communications network, Cellular radio coverage
- Online short term load forecasting for DSO
  - Forecasts can be used as pseudo measurements for State Estimation
- An efficient consumption optimisation for dense neighbourhood area demand management
- Flexible power application infrastructure (FPAI) implementation
- Derivation and implementation of the unified three phase branch models for modelling the grid topology.
- Prototype and implementation of the three-phase distribution system state estimation software, with support for a wide variety of measurement types, capable of computing the system state in near real-time.
- An evaluation of existing comm. networks was done from physical and topological perspective. Used protocols, redundancy mechanisms, scalability possibilities and security mechanisms were studied.
- Many kinds of different KPIs were studied, like power network key performance indicators, communication network key performance indicators, converged smart grid key performance indicators, economic key performance indicators and business KPIs. After defining these KPIs new methods for assessing the reliability of smart grids was laid out.
- Techno economic analysis is showing that convergence of communication and power grid network will not only have better technical properties, but it will result in more cost effective smart grid system as result of future proof optimised technical model.
2 A summary description of project context and objectives

2.1 SUNSEED project aim

The overall objective of the SUNSEED project was to propose an evolutionary approach to utilisation of already present communication networks from both energy and telecom operators. These should be suitably connected to form a converged communication infrastructure for future smart energy grids offering open services that are based on advanced measurement and control sensor nodes for DEG smart grid monitoring, and on intelligent analytics and visualisation tools.

In order to achieve the above overall objective, the SUNSEED project had 5 main objectives focusing on:

1. Establish practical, converged DSO-telecom, secure communications network solutions for smart distribution grids.
2. Develop advanced measurement and control sensor node to achieve real time smart distribution grid observability in a secure way.
3. Use intelligent analytics and visualisation tools to manage smart distribution grid resources.
4. New business models of converged DSO-telecom communications infrastructures for lower TCO.
5. Test, prove and demonstrate key elements on a large scale field trial.

The project work was divided in six Work Packages (WPs). While the WP 1 dealt with project management, WP 2 to WP 5 were of technical nature and are further described in this and next Chapter. The WP 6 dealt with dissemination activities and is further described under chapter 4 and 5 of this document. The coordination between the work packages can be seen from the pert diagram presented in Figure 1.

![SUNSEED pert diagram](image)

Figure 1: SUNSEED pert diagram

2.2 WP2 - Systems concept and business techno-economic analysis

The goal of WP2 was to evaluate existing communication networks in EP and TS from physical perspective, topological architecture, used protocols on L2-5, redundancy mechanisms, scalability possibilities and security mechanisms. In WP2 we identified key requirements for dense smart energy grid networks from communication networks perspective. We defined methodology and data formats for smart grid data collection from large number of nodes and proposed novel metrics tested on SUNSEED field trial. Also business models and techno-economic analysis of use cases was done.
The main objectives of WP2 were:

1. To evaluate existing DSO smart grid communication topologies, architectures and evaluate solutions for converged networking (WAN, FAN/NAN, HAN) with telecom operator.
2. To define distributed, prosumer oriented smart grid performance indicators for energy and communication networks in DSO and telecom environments.
3. To characterise business models in DEG smart grid stakeholder marketplace and do techno-economical DSO-telecom overlay communication networks TCO.

SUNSEED has determined smart grid architecture with various entities that communicate between each other, i.e. WAMS nodes (PMUs, SPMs and FPAlis), smart meters, message brokers (XMPP, MQTT and AMQP), data storage (MongoDB), forecasting services, state estimators, security solutions and visualization services (GIS). We prepared a field trial specification which included a detailed communication network design and architecting the building blocks (WAMS node) and key software modules in the top of the framework pyramid. We have compiled a set of communication technologies options (primary and secondary link) for smart distribution grid: fiber, 4G / LTE, RF mesh, xDSL, WiFi, PLC.

We defined distributed, prosumer oriented smart grid performance indicators for energy and communication networks in DSO and telecom environments. We present the description of devices, methods and key performance indicators (KPI) used in the SUNSEED field trial. A deep analysis of access technologies that could successfully satisfy most of important technical demands for smart grid was performed. The result was leading us to three different scenarios of synergies. The team touched multidimensional optimisation problem with decision tree modelling.

2.3 WP3 - Communication networking components and infrastructure of DEG smart grid

The goals of the WP3 were twofold. First, to design a proper communication networking solution, combining both, the distribution system operator and telecommunication operator existing networking infrastructure. The resulting solution should provide reliable and secure end-to-end networking services and fulfil the expected future requirements. The second goal was to design and prototype secure connectivity, measurement and control nodes, used in a trial to establish new services and validate particular approaches and solutions. More concretely, the WP3 goals were:

1. Determine the communication network and traffic requirements of the DEG, smart meters and other electricity grid related infrastructure, for the consequential design and real-time operation of future smart grid.
2. Derive methods and tools for proper dimensioning and design of existing communication technologies in order to support the traffic originated from the real-time smart grid operation.
3. To propose and implement a closely coupled communication network and electricity grid solution that will support precise measurements as well as real-time control of individual components, taking into consideration technologies such as smart meters and wireless sensor networks.
4. Design and propose end-to-end security solution that enables secure and easy deployment of (measurement) nodes in the distribution grid, flexible authorisation procedures, and secure communication.
5. Design, implement, prototype and validate in laboratory environment the measurement and control nodes taking advantage of the networking solution to establish real-time grid observability and individual loads management according to the needs of users and/or status of the grid.

The first task defined the necessary inputs that were required for the other task in the work-package. These inputs are: the traffic model (especially for the WAMS modules), control loops of the future smart grid and their corresponding communication requirements, different types of smart grid control implementations as well as candidate networking solutions for support of the real-time smart grid operations.
The second task defined evaluation methods for quantifying the achievable communication delay vs number of supported nodes and given the amount of available resources in the wireless access network reserved for the smart grid support. Further, analytical models were derived for quantifying the access network bottleneck (i.e. outage probability) of the random access and uplink/downlink shared data channels. Regarding reducing the collision probability in 802.11ah networks a station grouping algorithm is proposed. This task also investigated the impact of the packet delivery reliability (for a given delay budget) when packets are transmitted over multiple networks in parallel (i.e. multi-interface transmission). An approach is also presented about joint-design for secure and robust networking using the existing networking infrastructure at the telecom operator and the smart grid operator.

The third task dealt with the design of measurement and control nodes to support various smart grid applications (e.g. grid state estimation, flexible loads control) and provide respective data collection for further analysis. The two WAMS node instances that were produced as an outcome of this task share the same application and connectivity framework and two distinctive measurement and control modules to support on one hand the power quality (PMC) and synchrophasor (SPM) estimation and on the other hand direct on/off or application level loads control. Next to the WAMS node development this task also provided the detailed specifications of the communication networking solution and measurement data collection for the SUNSEED trial.

The fourth task designed the security solution for the future smart grid applications. This security solution ultimate goal was to secure the communication between the WAMS devices and the SUNSEED application. The work involved had 3 main focuses:

- Enhanced security of the credentials stored in the devices thanks to an embedded secure element soldered on the WAMS PCB.
- A unified management for access control and credential distribution system, articulated around an authorization server.
- The definition of ‘plug-n-play’ initial security bootstrap procedures for the WAMS node installation as well as for the application security initialization. This procedure involves the preprovisionning of initial secrets inside the secure element. Those secrets are used automatically during the device deployment phase to derive shorter terms credentials to be used to secure WAMS communication and enable WAMS access to protected resources.

2.4 WP4 - Integrated control, management and analytics

The goal of WP 4 is to develop a platform for real-time analytics, forecasting and management services for energy distribution networks for small DSOs, in order to significantly improve the observability of the distribution grid, as it is one of the key challenges in the context of introducing smart grids.

The following main objectives were defined in WP 4, which are aligned with four tasks composing the WP4:

1. To develop a detailed model of DSO grid that will enable the observation of loads on a micro level as well as serve as a tool for the simulation of different measures.
2. To implement short-term demand-response forecasting models for efficient planning and management of energy flows.
3. To develop a central system for managing energy consumption and production in accordance with the observed patterns and criteria to minimize energy peak situation.
4. Extend and adapt the Flexible Power Application Infrastructure platform to operate in the DSOs smart grid.

Within the first task we aimed to develop the detailed DSO grid model, comprising of electrical specifications of network elements (e.g. lines, transformers, ...) and also the user/producer profiles
including device profiles (e.g. storages, time shifters, buffers, ...). To achieve the full observability, the three phase state estimation for distribution system was envisaged, based on measurements from WAMS-SPM, developed in WP 3, and from Smart meters. In addition, all the current/forecasted grid status is displayed in a geographically distributed manner using GIS, as well as dedicated visualisation tools.

The goal of the second task was to develop algorithms and system for forecasting, based on the measurements, calculations and devices status provided in first task. The developed system needs to include services for acquisition, cleaning and fusion of data, coming from a variety of data sources in different formats, data modalities and of varying quality. Developed algorithms for cleaning, fusion and prediction will be based on techniques from semi-supervised machine learning, offering ability for domain experts to provide feedback as part of the learning process. The developed algorithms need to be designed to run in real-time.

The third task was dedicated to smart grid management, where we study, evaluate and select the load coordination and management mechanisms to better support DEG integration. In addition, integration of software modules namely grid model with state estimation, load forecasting and Flexible power application infrastructure will be done.

Within the fourth task we aimed to develop the on-site light-weight node software, integrated securely with the WAMS node, and central system based on TNO’s Flexible Power Application Infrastructure (FPAI) that acts as a M2M-based interoperability layer between the Load Management System and the distributed energy resources. It should support Internet-of-Things properties (registry & automatic discovery of connected resources and nodes), management interface to remotely manage on-site nodes and a monitor and control interface to monitor the grid and control on-site nodes in a secure manner.

2.5 WP5 - Field trial integration and validation

WP5 focuses on the planning, preparation and execution of the test polygon that will allow analysis of the strengths of the concepts and techniques developed in WP2, WP3 and WP4 in practice. The main goal of this WP is to physically setup, run and validate operation of large scale field trial. Deployment and validation of the use case scenarios is defined, and applications deployed and verified within.

Work in WP 5 is divided on four tasks to achieve following main work package objectives:

1. To set up field trial consisting of approximately 1000 measurement nodes at DEG, substations, mobile base stations, homes, business sites, e-car charging points.
2. To perform long term accurate power flow measurements and communication traffic flow measurements at these locations.
3. To extract lessons learned and quantify results and show the scaling to deployment (plan, operate, finance) of similar or larger scale smart grid energy and communication systems.

In first task the field trial location were selected base on independent criteria to bind as many possible existing and future communication network and cover all relevant SUNSEED use cases. The selected network parts have to integrate future prosumers with number of different DER in rural and urban area and have to represent rounded part of power grid. All these demands are covered in selected field trial locations Kromberk, Bonifika, Razdroto and Kneža. In this task we prepare first preliminary results from DSO and telco communication network coverage analysis. Topological analysis of EP and TS networks shows a high degree of overlap, with wireline and cellular communication networks. On this basis we prepare the communication solution scenarios and preliminary installation plan for connecting end nodes for all distribution grid filed trial locations: smart meters and WAMS-SPM devices with PMU capability.
A crucial task in WP5 was second one where field trial was set up with installations of smart meters and developed power measurement equipment (WAMS SPM devices). In total we have installed of 38 pieces of WAMS SPM devices on 30 different geographical locations and 781 of residential smart meters with 24 PLC data concentrators. For measurement data transfer to smart meter and WAMS database a special communication network architecture was developed with different communication scenarios including FTTH, mobile (GPRS, EDGE, UMTS, LTE), satellite and PLC. All measurements from the field trial are accessible and visible on GIS portal (SunGIS).

In third task a comprehensive field trial analyses and validation was made. We focus on physical installations on field trial, communication network with developed communication solutions and for power measurements as inputs for developed applications. Regarding the physical installation some deviations regarding first installation plans occur due to several unpredictable technical and non-technical reasons which are explained in D5.3. On communication field we found out that fiber and also LTE technology achieve high performance. Evaluation of power measurements supporting the distribution system state estimation and load forecast shows that magnitude error is smaller than 0.2 % and phase error is below 0.01 degrees. Prediction evaluation shows that regression models work only slightly better than moving average models at very short and at longer prediction horizon.

In last fourth task an evaluation of all solutions and results for converged DSO-telecom communication network supporting future smart grids was made. We produce and publish (D5.4) a Smart grid converged DSO-telecom communication network deployment guide book with all recommendations for installation, communication and power measurements application solutions obtained in research and practise work done in whole project.
3 A description of the main S&T results / foreground

3.1 WP2 - Systems concept and business techno-economic analysis

First goal of WP2 was to identify key requirements for dense smart energy grid networks from communication networks perspective. An evaluation of existing communication networks in EP and TS was done from physical perspective. Topological architecture, used protocols on L2-5, redundancy mechanisms, scalability possibilities and security mechanisms were studied. Based on the evaluation we were able to proceed with field trial specification, its detailed communication network design and design the building blocks (WAMS node) and key software modules in the top of the framework pyramid.

A systematic analysis of possible developments in distribution grid is based on three types of use cases:

- UC-1 with a dense network of measurement nodes, smart meters and WAMS, on all DER nodes and majority of prosumer locations that will greatly enhance distribution grid observability
- UC-2 presents use of real time communication and time synchronous measurements (from 1 s to 15 min reporting intervals) as the solution towards advanced distribution management system with capabilities up to date seen only in transmission grid (e.g. voltage profile from state estimation);
- UC-3 studies the combined use of converged communication and power networks to pinpoint the type and location of failures. Particular implementations and solutions based on these use cases will be physically realised also on field trial.

Technical requirements for communication networks in smart distribution grid present a starting point of the necessary functionalities. Achieving QoS as demanded by characteristics of elements and systems in distribution grid is essential in future smart grids, particularly those based on converged networks. We have addressed security measure requirements from wider perspective covering data management, communication, confidentiality, integrity, availability, disaster recovery, identification, authentication, authorisation and risk management. Additionally, IP/MPLS technology is explained as the communications network core.

We prepared a field trial specification which included a detailed communication network design and architecting the building blocks (WAMS node) and key software modules in the top of the framework pyramid. We have compiled a set of communication technologies options (primary and secondary link) for smart distribution grid: fiber, 4G / LTE, RF mesh, xDSL, WiFi, PLC. Communication providers are utility, telecom operator or 3rd party (second telecom operator, municipality) based on WP5 field trial specifications.

Based on WP5 Field trial concept and definition, we have compiled a set of communication technologies options (primary and secondary link) for smart distribution grid: fiber, 4G / LTE, RF mesh, xDSL, WiFi, PLC. Communication providers are utility, telecom operator or 3rd party (second telecom operator, municipality). We have identified and refined general communication requirements which are:

- L3 networking by default (from transformer station or WiFi NAN node uplink),
- Cellular (mobile) access via APN and LTE, with specific APN per geo_area / node_type / interface_type, Latency (operational delay) constrained comms networks with targets: < 100 ms (time synch), < 1 sec (state estimation),
- All transformer stations with dual / redundant uplink communication paths,
- Multilayer security solutions (e.g. L2 = access control lists, L2.5 = MPLS, L7 = eUICC integrated within each WAMS node).
SUNSEED has determined smart grid architecture with various entities that communicate between each other, i.e. WAMS nodes (PMUs, SPMs and FPAIs), smart meters, message brokers (XMPP, MQTT and AMQP), data storage (MongoDB), forecasting services, state estimators, security solutions and visualization services (GIS).

![Diagram of SUNSEED smart grid architecture](image)

**Figure 2:** Systems architecture view and key building blocks of SUNSEED.

We were building upon the known standards in smart grid realm, particularly IEC 61850 and Smart Grid Architecture Model (SGAM) defined by IEC. The state of the art in communication networks for smart grid in WAN and NAN is covering also technical characteristics of solutions being used to date. PLC has a particular role in AMI and will undoubtably continue to be main technology of choice for communication from smart meters to first aggregation point (usually PLC concentrator). Analysis of contemporary DSO and telecom operator networks reveals interesting similarities (e.g. use of MPLS, timing synchronisation mechanism) and these will be put to use in designing converged networking solutions. DSO uses physically different networks to transport different traffic types, to assure performance or make access secure (e.g. control/command, teleprotection, data centre access, AMI collection).

To achieve integration of multitude information flows within converged DSO – telecom operator communication network it is mandatory to strictly follow the good practices of traffic classification from source, WAMS node, throughout the network and to its destination in DEMS. Such operation can provide QoS as required by DSO for reliable and secure operation of distribution grid. MPLS is the central logical interconnect from WAMS nodes to telecom operator testing and data servers and also to other entities (e.g. DSO). The extension of current EP and TS approaches was implemented in the field trial. Most of the communication between WAMS nodes and the TS datacentre (where raw storage was established) was separated from public internet using multiple APNs (connection via mobile networks) and VPNs (xDSL and satellite connections). Core network data was terminated with firewalls (for securing connectivity toward MPLS network) and load balancers (for distributing workloads across multiple computing resources).
The second goal of WP2 was to define methodology and data formats for smart grid data collection from large number of nodes and to propose novel metrics tested on SUNSEED field trial. Thus, we defined distributed, prosumer oriented smart grid performance indicators for energy and communication networks in DSO and telecom environments. Deliverable D2.2.2 is presenting the description of devices, methods and key performance indicators (KPI) used in the SUNSEED field trial. The majority of expertise was performed on “new methods and tools for assessing the reliability of Smartgrids” and corresponding “data collection”. KPIs are as follows:

- KPI of power networks present IEEE 1366 specified system interruption indices (e.g. SAIDI, SAIFI, MAIFI) and EN 50160 specified power quality indices for medium and low voltage distribution networks.
- Communication networks KPI describe classical physical layer ones (e.g. latency, jitter, packet loss), mention relevant IETF proposed recommendations.

Data for defining the KPIs is collected at specific locations, e.g. substations, medium and low voltage bus bars, distributed energy sources and prosumer locations. Reporting period for WAMS nodes was about one second which is significantly shorter compared to smart meters’.

Data collection framework and analytical data processing derived KPIs, distribution network operations parameters (e.g. voltage profile in substation graph) and forecasts of grid state and loads. We were using so called Advanced distribution network management system platform to generalise the field trial operations on a model use case that collect and summarise all main points of the field trial operations that we want to investigate. We did this for:

- dense placement of distributed energy resources within distribution grid,
- achieving distribution grid observability,
- tracing operations and faults via power grid and supporting converged communication networks,
- integrating processed information for real time visual presentation within advanced energy management centre.

Key measurement and communication requirements of WAMS were discussed with a large focus on fast reporting (1 second) of multiple measured parameters: U, I, P, Q, harmonics. We found out that communication network connection, architected for redundant and highly reliable, dual physical port operation must support different treatment, prioritization and marking of data traffic, i.e. measurement vs. control vs. internet.

The transition from a classical, passive distribution grid to an active, “smart” grid usually implies the addition of various telecommunications and IT components. This can have a significant impact on the performance and stability of the grid, but it is not easy to say if this will be positive or negative. More components means more failures, but smart control strategies can also limit the impact of failures, for instance by fault isolation or by power rerouting. Careful analysis, for instance by simulations, should be performed to assure that the performance of the grid will not be degraded by the transition.

A grid in which sensors, controllable (power) components, telecommunication links and control nodes work together can be viewed as a dynamic system with one or more feedback loops (in the sense of the classical control theory). For predicting the behaviour of such systems, one has to study the system as a whole, including the closed feedback loop(s). One cannot predict the behaviour, including the expected performance, by studying individual sub systems (power grid, telecommunications network, control algorithms) since this ignores the closed-loop nature.

Except for trivial designs, it is hard to evaluate the performance of the complete system when being affected by (random) failures without looking into the different failure scenarios individually. Each failure
scenario (combination of one or more failures) may cause a different response from the feedback system and may have a different outcome for the performance. The proposed method is based on the systematic simulation of a large number (but not all) of those failure scenarios, up to the point where sufficient accuracy has been reached. The basic principle of this method has been used before successfully for the evaluation of the performance of large telecommunications core networks.

Figure 3: Simplified view of the architecture of the tool set

A number of candidate power flow analysis tools (GridlabD, OpenDSS, MatPower) have been identified for these simulations. Some experiments with GridlabD have shown that it is possible to integrate this tool into an evaluation system that implements the described method of systematic but incomplete failure scenario simulations. An important question that has not been answered yet is whether the proposed method is scalable enough to handle the complexity and number of components of a typical “smart” distribution grid, such that sufficient accuracy can be reached within reasonable computation time.

The third goal was to characterise business models in smart grid stakeholders marketplace and to do techno-economical DSO-Telecom overlay of communications networks total cost of ownership.

We did analysis of different scenarios of today’s owners of infrastructure, the DSOs and Telecom’s. In the beginning we started with ToC preparation of the final deliverables in this task, which are D2.3.2 and D2.3.4. SUNSEED partners were discussing and then at the end we have defined all possible stakeholders, which were then involved in the techno-economical modelling. Typical business case scenarios were defined. They mainly distinct between Telecom and DSO cooperation:

1. utility takes all roles,
2. utility extends today’s operation, telco takes all ICT roles,
3. complete market democratisation

We have performed a deep analysis of access technologies that could successfully satisfy most of important technical demands for smart grid. The result was leading us to three different scenarios of synergies. The team touched multidimensional optimisation problem with decision tree modelling.

We used five-step procedure in techno economic analysis. The first step was the definition of informational flows, second was to get the best combinations and common properties, third step was using ICT tools for decision tree, evaluated everything in fourth step and we got results in fifth. Investment costs of different methodologies like incremental costs, long run costs and LRIC model were also analysed.
Field trial communication solutions represent valuable missing input for business and economics analysis of the project. We included results from the field-trial and experiences we gain into deliverables. We needed to understand this to analyse the stakeholder's involvements. The filed trial (M30-M36) showed us a valuable insights for better understandings of different stakeholders roles in multidimensional model.

![Diagram of field trial communication solutions](image)

Figure 4: Business model 1 - Utility takes all roles.

New business models were prepared and developed. This business models connect technology and business mainly between energy utilities and ICT companies and then we have added other stakeholders (service offering) on future smart grid market to have more accurate models. We used these as direct input for the scalable cases when we define the end-2-end value chain between DSO, telecom operator, energy services provider, ISP, and/or 3rd party solutions provider (e.g. data analytics solution provider). We have done detailed analysis with LRIC methodology on specific use cases which we discovered and see in field trial.

We performed a market analysis of important stakeholders participating in proposed new business models. We have found synergies between DSO (energy) and telecom operators with regard to end customer and evaluation of different business models. This task had a significant influence because energy M2M/Smartgrid vertical became one of most promising future combined telco-DSO ecosystems. Working on the project and exploring multidimensional design space presented us with a limited set of possible scenarios taking into account local governmental influence and activities. These scenarios we’re economically evaluated with long run incremental cost analysis. Telecom operators will need to change business models dealing with energy companies, if they would like to be a part of new ecosystem, implementing new SLAs and managing trust for multiple stakeholders.
3.2 WP3 - Communication networking components and infrastructure of DEG smart grid

The goal of WP3 was to (i) develop a robust, secure and future proof networking solution for real-time management of the smart grid, (ii) design and implement the grid monitoring devices, and (iii) propose and adopt a new end-to-end security solution. For this purpose, the following key results were achieved.

As illustrated in Figure 5, future smart-grids will have a real-time management loop that is based on various measurement information collected from the installed power grid measurement nodes. WP3 has made a proposal regarding different types of smart grid control loops i.e. centralized, distributed (as shown in Figure 5 in the bottom right corner), and localized as well as communication requirements for these control-loop types. Further, for the Wide Area Monitoring System (WAMS) nodes that are also developed in this work package a traffic model is proposed as illustrated in Figure 5 (bottom left corner). The communication requirements and the traffic models were used as an important input for the design and analysis of the communication networking solutions in this work package.

Further, the candidate access network technologies (wired and wireless) were selected and their pros and cons analysed for the support of future smart-grid applications. For the wireless access networks, the initial capacity and delay bottleneck insights were used to select LTE as primary technology (UMTS and WiFi 802.11ah as secondary) to be further investigated in detail.
Having selected LTE as the primary technology, the LTE access network was analysed from various perspectives, namely:

- A coverage assessment where generic deployment scenarios where considered given specific parameters such as anticipated device deployment density and frequency bands for the field trial networks. The analysis also considered the effect of various coverage enhancement techniques;
- LTE and NB-IoT delay-based capacity assessment, which took a starting point in the coverage assessments and further evaluated the amount of resources required by devices in different coverage conditions, which finally allowed to evaluate the statistics of the latency;
- Whenever an idle LTE UE wishes to make an uplink transmission, e.g. to report a power measurement, it needs to go through the message exchange of the access reservation protocol outlined in Figure 6 (right). Since the different messages are transferred in several of LTE’s resource limited logical channels, we identified a potential bottleneck problem. To be able to thoroughly analyse the potentially difficult scenarios, we proposed an analytical model that accurately accounts for the limited resources and retransmissions taking place in case of collisions or failed access attempts.

These analyses revealed that LTE cannot reliably support real-time smart grid applications in all circumstances, for example during peak cell load or in case of weak signal coverage. Therefore, several proposals for re-engineering of the LTE and other access solutions have been investigated. Specifically, the following access protocol improvements and access strategies have been proposed:

- Massive M2M access with reliability guarantees in LTE systems
- Transmission probability control and two-hop ALOHA
- Reliable reporting in LTE with periodic resource pooling

These proposed improvements are targeting the case of random uplink access for a massive number of devices. While this is not directly applicable for the deployed WAMS-SPM devices, as long as they are functioning with short transmission interval (<10 s), the massive access problems occur in general smart grid systems when various sensors and IoT devices are reporting measurements.

A different proposed improvement considers different ways of exploiting multiple network interfaces, such as LTE, UMTS, and Wi-Fi simultaneously, in order to improve the reliability of real-time critical applications. (see Figure 6) Besides the most straightforward packet duplication or cloning strategy, we also considered packet splitting strategies that relied on a fountain code to generate redundant packet fragments. Based on this fountain code, we investigated the applicability of k-out-of-n strategies and latency optimized strategies, which in some cases allowed to decrease, e.g. the 99th percentile latency by as much as 40%, when using low-rate technologies such as GPRS and EDGE with relative large payload sizes (>1500 bytes).

In addition to the 3GPP based access network solutions, the work in SUNSEED also studied the newly released IEEE 802.11ah protocol. A key problem in IEEE 802.11 based systems is the collided transmissions caused by the hidden node problem. To mitigate this problem, a novel station re-grouping algorithm was proposed.
To support the project use cases requiring real-time information on the grid state, the prototype measurement and control nodes of the Wide Area Measurement System (WAMS) were designed and implemented. In this process, the aim was to best fulfil the following objectives that are often characterized by conflicting requirements:

- Fulfil the particular requirements of distribution system operator.
- Combine several WAN and LAN communication interfaces.
- Support power quality and synchro-phasor measurements.
- Support direct on/off and application level loads control.
- Support gateway functionality for a selected set of underlying devices.
- Enable batch remote software reconfiguration, deployment and updating.
- Adopt specific components partially developed within the project.
- Adopt security solution.
- Introduce a common application framework supporting parallel hardware and software developments of different partners.
- Support FPAI framework.
- Modular node design with single compact form factor and several installation variants.
- Device by device extensibility via proprietary bus.
- Fully embedded functionalities requiring minimum external installation components.
- Support standardized legacy and IoT protocols.

The purpose of the developed prototypes was to (i) support particular developments and emulate the use cases in laboratory environment and (ii) consequently deploy the final prototype instances in the actual field trial. Following a modular hardware and software design concept, a set of modules with corresponding functionalities have been designed that in different combinations form the instances of synchro-phasor measurement device (CP-SPM, also referred to WAMS-SPM) and power quality measurement and control device (CP-PMC, also referred to WAMS-PMC). As depicted in Figure 1 (Figure 7), both of those share the same application and connectivity module with various component placement options and a distinct version of the measurement and control board.
The CP-SPMs are dedicated devices with common time reference provided by a very high precision GNSS driven clock, which allow for time-synchronized phasor (synchrophasor) estimations at different locations. Combining high precision and high sampling rate (up to 50/60 Hz) measurements of voltage or current phasors on a 3-phases system allows for a comprehensive view on the state of the entire grid interconnection. The prototyped CP-SPM enables 3-phase voltage/current synchrophasor measurements at medium/low voltage of the distribution grid. Besides dedicated measurement circuitry and signal processing it also features a Linux-enabled application processor, LTE, Ethernet and low-power radio communication interfaces, secure element, and a GPS-based reference clock. The CP-PMC devices allow for 3-phase power quality measurements (such as real/reactive/apparent power, frequency, voltage, current, total harmonic distortion) and control of end connection points (via on/off relays or serial line application interface). Within the project, the devices were designed in exactly the same form factor as CP-SPM, reusing the application and connectivity boards and introducing a measurement and control board. The 1 s reporting period was considered for devices deployed at major grid buses and important prosumer locations to support state estimation, while a request-response mechanism based on FPAI framework was considered to support demand-response services. More details on the design of CP-SPM and CP-PMC devices can be found in reports complementing the deliverables D3.3.1 and D3.3.3.

In field trial, the CP-SPM and CP-PMC devices were together with smart meters deployed in 4 clusters. Apart those being characterized by different grid characteristics and used to investigate complementary use cases for grid management, different connectivity options have as well been considered. Those are together with wiring diagrams for CP-SPM and CP-PMC reported in detail in D3.3.2.

The SUNSEED solution for real-time management of the future smart grids involves deployment of numerous WAMS nodes that continuously monitor the functioning of the distribution grid. The deployment of these WAMS nodes in practice should be as automated as possible or actually in a ‘plug & play’ fashion. This also includes the notion of “plug and play” security. In principle this ‘plug & play’ concept is not new, and yet within SUNSEED it is deployed for Internet-of-Things (IoT) applications, which is an enhancement of the state of the art. The whole security solution is illustrated in Figure 8.

During the manufacturing process the secure element is embedded in the WAMS node containing the security secrets for that particular device. These secrets are used for device authentication (i.e. preventing cloning) after the node is deployed in the smart grid. Additionally, the associated authorisation credential and security parameters are loaded in the authorisation server.

Then, after the node deployment the ‘plug & play’ approach is realized via the initial security bootstrap procedure where the device is authenticate and all relevant security parameters are made to the device for e.g. securing the communication links and for the sub-sequent applications security managing the publish-subscribe access to the data produced by the node.
The designed security procedure was tested in the SUNSEED trial via the state-estimation use case and the deployment of the WAMS-SPM nodes, where the secure element was embedded. The trial showed that the designed solution is feasible and workable for practical deployments.

![Security Solution Architecture](image_url)

**Figure 8: Security Solution Architecture**

### 3.3 WP4 - Integrated control, management and analytics

One of the major goals of the SUNSEED project is to improve the observability of the distribution grid. The improved observability is one of the key challenges in the context of introducing smart grids. To avoid high investment costs into reinforced grid the grid requires some smartness, where all decisions are based on the in real time estimated state of the grid and as well on the forecasted state of the grid. From the DSOs perspective the observability is in particular important because it allows higher penetration of distributed resources into the grid. Further, the operation of the grid is followed closely and disturbances can be observed and eliminated at the place of their origin. We use the observability for the sole purpose of observing the network and as an input into the forecasting and grid management module that supports decisions made by the operator in the distribution control centre. We achieve observability of the network by estimating all the electrical parameters on the network elements in the network. The data flow model of Analytical platform developed within WP 4 is depicted in Figure 9.

Developed three phase state estimation software, which supports a wide variety of measurement types, is capable of computing the system state in near real-time. Its performance depends on (i) the accuracy of the measurements, obtained by smart meters and custom developed synchro-phasor measurement units (WAMS-SPMs), and (ii) on the parameters of the network model. Thus, for the DSO grid model series impedance and shunt admittance matrices were developed for all underground cables and overhead lines focusing to Kromberk testbed. They were then used in the proposed unified three-phase model for distribution network components that we implemented in the power flow and state estimation solvers and used in practice. This representation of network components allows straightforward construction of the network admittance matrix. Three phase state estimation engine software architecture in C++ programming language was developed, considering parallelization that could be done in the future. It is
based on a nonlinear Weighted Least Square (WLS) approach. The state estimation was successfully tested using real measurements from the Kromberk deployment site (Figure 10). To find the optimal number and positions of WAMS-SPMs we perform multi objective optimisation algorithm as there are too many possible solutions to evaluate them all. In addition, we also performed the sensitivity analysis of the state estimation problem, for which several different methodologies were implemented and compared.

In SUNSEED, grid management mechanisms are considered primarily from the DSO perspective whose main aim is to provide means for safe grid operation. We focused on methods to optimise the voltage on the network with the objective to reduce network losses by using measurements from devices (WAMS, SM) placed on the low and medium voltage. The proposed method utilises a Greedy Algorithm and power flow analysis to find the tap position of the transformer in the primary substation that produces the lowest losses. The proposed method for voltage optimisation enabled by monitoring the voltage has been simulated for a trial network from the SUNSEED project. The results show that method reduced the MV and LV network power losses by 6.29 %. This result is expected to be higher for distribution networks where the difference between maximum generation and maximum demand is higher or for networks where the demand/generation varies more frequently. Another smart grid management mechanism that was investigated was an optimisation framework for massive household consumption load management. We also focused on mean field game modelling electrical vehicle charging, where we proposed a novel game theoretic framework for massive EV charging scenario.
Figure 10: State estimation with voltage profile visualization

Figure 11: SunGIS screenshot
In the developed data visualization module a unified view, i.e. integral presentation of power grid, and communication network coverage, together with power grid elements and communication network elements, i.e. assets from telecom operator and electrical utility was made. In addition to the presentation of static layers the majority of the measured data and results (state estimation, predictions) are also represented in the data visualization system based on the GIS software. Due to amount and dynamicity of data, highly efficient system capable of processing real-time data is required. Therefore we prepared a combination of an open source software web-based GIS framework and already developed open source based application mGISmap, used as a graphical presentation platform, capable of presenting real-time data of both power grid and communication network locations, eg. power flows, radio coverage of distribution grids etc. GIS layers of DSO and telco are integrated into single GIS application, ie. SunGIS. As well, dynamic data layers are collecting and presenting data from various sources (from partner software modules, SUNSEED databases (Mongo), external databases, monitoring systems etc.) in real-time. In addition to main visualisation module (SunGIS) we developed also some dedicated visualisation tools for forecasting and FPAI, allowing additional features and analytical tools.

Large amount of data needs to be transferred, organized and queried from arbitrary sources (eg. WAMS, smart meters, etc.) to common database where data is available for presentation or any other further data processing required for smart grid operation, eg. forecasting, state estimations etc. In order to assure high performance system, besides database design the other challenge was implementation of communication interface which also includes message broker backend and service delivery broker. Implementation of common database (store engine) was designed based on MongoDB, where type of data was considered. We choose MongoDB due to its ability to insert messages fast as possible, regarding any relational information.

In terms of communication interface sub-system, internal message queuing system was deployed to better cope with large input and output data. Possible security issues related to data transfer in-between entities which use database system and within the elements of database system were evaluated as well. Different security mechanisms could be applied, while with respect to network concept, following security elements were considered: access control (authentication, authorization), virtual private networks, HTTP API authentication and private access point names within mobile network (private APNs).

We presented performance results of message queuing middleware, which confirmed high-performance of internal routing. Also, some approaches (sharding, clustering) towards high-availability of data was presented and tested on MongoDB system.

Forecasting module is one of the crucial building blocks in smart grids with applications such as load switching and optimisation, estimating pseudo measurements for state estimation, decision support for power systems operations, maintenance planning and trend detection. In the past experienced system operators were able to predict load requirements. Now, dynamic complexity of load, expansion of renewable sources, proactive devices, stricter power quality requirements, and deregulation are mandating the development of advanced forecasting tools. In SUNSEED project we have developed a decentralized, data-driven, streaming models, capable of processing large amount of real-time heterogeneous data streams and produce predictions on various nodes in the grid, from 5s to 24h into the future.

In order to build the most effective model for the specific power grid (they differ in geographical properties, meteorological factors, grid topology, etc.), detailed exploratory data analysis was firstly done, which helped us identify relevant features. Beside the real-time grid measurements data provided by the partner Elektro Primorska (from AMI smart meters and WAMS meters), two additional external data sources were taken into account: static date-time data (time of day, working day, holiday status, etc.) and weather data.
(current measurements and forecasts). For each data source additional streaming data aggregates were developed for the purpose of data cleaning, pre-processing and data enrichment. Prototype also includes REST API services for posting and requesting the latest results to the main database.

Data enrichment was performed by feature engineering. Several additional features that were identified as possibly relevant (from the exploratory analysis) were created, such as “hour of day”, “day of week”, “weekends”, “holiday status”, “day before holiday”... From the time series data (measurements, weather), several additional moving statistics aggregates were computed (mean, min, max, variance) and analysed, for different time windows (1h, 6h, day, week, month). In order to identify the most valuable and important features, importances were computed for all the extracted features for different prediction horizons and for different nodes (with different levels of load aggregation). Analysis shows that beside the real time measurements data, static data such as “date-time” features and “holidays” are the most valuable features. Including weather forecasts might also improve accuracy, but not significantly. Results were also used for feature selection, in order to reduce complexity and discard irrelevant or redundant features, which resulted in simpler models, shorter training times and reduced overfitting.

![Figure 12: Forecasting visualization](image)

Various data driven machine learning models (Ridge Regression, K Nearest Neighbours, Random Forest Regressor, Support Vector Regressor) were trained and evaluated with different feature sets, in order to find the most appropriate combination of method and constructed feature set. Results show that Ridge Regression model and Random Forest models produce the most promising results in terms of prediction accuracy, speed and model complexity. Further analysis also reveals that Random Forests tends to use special features (such as holiday status) better, and therefore produces better forecasts for non-regular days (such as holidays), but the model is more difficult to interpret. Evaluation analysis results also show that the forecast accuracy decreases with forecasting horizon, meaning that the further into the future we are predicting - the worse the prediction, which is intuitive. And furthermore, lower aggregation nodes performance at the individual level show much higher results (around 40% MAPE), than with higher level nodes (around 10 % MAPE or less).

The outcome of the extensive analysis (reported in D4.2.1) was a clear stack of technologies and prototype architecture needed for the development of the final prototype (presented in detail D4.2.2). The architecture of the prototype (built on top of the QMiner framework) was designed to be able to process a
large-scale heterogeneous data streams, from multiple data sources in an online fashion (using only online streaming algorithms). Two main components are the Data instance (responsible for online handling data streams – cleaning, pre-processing, feature engineering) and Modelling instance which includes mechanisms and algorithms for online forecasting (such as “store generator”, “load manager”, “receiver”, “merger”, “resampler”, “meta-merger”).

Final load forecasting module prototype contains several decentralized models (for each sensor node from low and mid voltage grid), and covers important use cases:

- **short term load forecasting (STLF)**: the main data source for the STLF are smart meter (AMI) measurements (data is sent once per day for 750 different nodes). Based on this data source, the model is able to forecast the load for specific node for various prediction horizons; from 1h to 24h into the future. This predictions will be used as “up to date” estimation of the grid, as pseudo measurements for State Estimation module (described in D4.1.1), since smart meter measurements are usually already obsolete at the time of the estimation (since they are sent only once per day).

- **very short term load forecasting (VSTLF)**: for the VSTLF model, the main data source are WAMS (Wide Area Measurement System) measurement units, with a much higher frequency (50Hz) streaming for 16 nodes, which generate vast amounts of data (1GB per day per unit). In this case, the model is calculating very short term predictions - from 5s to 15min into the future. The result of this model will be displayed on GIS and could be used by higher level applications such as Autonomous load management module (described in D2.2.1).

- **user profiling**: the main data source are smart meter (AMI) measurements. Weekly and daily consumption profiles (histograms) are calculated for all nodes, once per day, which give an expert user additional introspection into the behaviour of a certain consumer. This information is useful to grid operators for grid management, planning and maintenance.

To ensure the scalability of the system, prototype also enables simple parallelization (running different sets of models on different instances; in current setup we are running one instance for 5 seconds event horizon and another for all other models) due to its decentralized architecture. Instances could be run anywhere within the closed network, where consummation of MQTT data is available.

All the results from the analytics and forecasting module are stored into the common central database, from where it is available to other modules such as state estimation and autonomous load management module, and finally for the purpose of visualisation in GIS. Additionally, local GUI server was developed for the purpose of testing and investing of the results. Several data visualization tools were developed and added to the GUI for demonstration purposes.

One of the WP4 objectives was also to develop light-weight software for the Wide Area Measurement System (WAMS) nodes that perform measurements on the electricity network and to develop a central node management system. Both of these based on TNO’s Flexible Power Application Infrastructure (FPAI) and using IoT concepts to allow the automatic deployment of hundreds or thousands of nodes.

To achieve this, a SUNSEED architecture was developed based on IoT concepts that allows:

- The discovery of WAMS nodes, smart meter nodes and power consuming devices.
- Collection of relevant information from the discovered nodes (WAMS measurements, smart meter measurements, power consumption profiles).
- Distribution of the information of the discovered nodes to subscribed applications.
- The integration with the security solution developed by another partner within the SUNSEED project.

The deployment of this architecture is sketched in Figure 13.
An XMPP server (openfire) was implemented at the datacentre of Telecom Slovenije supporting the publish/subscribe mechanism and authentication using certificates. A provisioning server (acting as a resource server proxy) was implemented to enable the security framework when using XMPP. This provisioning server acts as a gateway between the authorization server and the XMPP server, allowing the authorization server to control the resources (the publish/subscribe nodes) in the XMPP server using a
number of APIs. A registry was developed and implemented to implement the IoT discovery allowing WAMS device to register themselves an ownership of the devices to be claimed if appropriate.

An FPAI management centre was developed and implemented so that the many FPAI clients (WAMS nodes) can be managed group wise (which FPAI clients belong to which group can be specified freely). Each FPAI clients regularly checks the FPAI management centre (using the TR69 protocol) to see if new software/configuration is available and implements this. The management centre also shows when the client last reported to the management centre thereby monitoring the health of the FPAI nodes. In Figure 14 a screenshot of the FPAI management centre can be seen with one client not having reported for a longer period of time, shown by the red filling.

At the WAMS side the FPAI software has been adapted in a number of ways:

- Semantic descriptions of the measurement modules and actuators have been developed to make them easily available for applications to use. For the WAMS modules this has been implemented as a new FPAI interface.
- The FPAI interfaces have been adapted to XML models so that the FPAI interfaces becomes easier to use and implemented with a variety of communication protocols.
- An XMPP FPAI client that implement the required XMPP interface was developed and implemented.
- The FPAI client has been implemented on the WAMS modules and has been adapted to read the measurements directly from these modules. This in effect means the creation of an XMPP based measurement module that uses XMPP IoT extensions to register with the XMPP server and send measurements to the XMPP server.
- The FPAI client has been extended to use the secure element when available to store the private key and to generate the necessary information to set-up a certificate based TLS connection with the XMPP server.
- The FPAI management centre client software to was adapted to ensure uninterrupted operation of the FPAI nodes in the event of rebooting of the WAMS nodes.

In the field trial 5 WAMS PMC nodes in the TNO lab, 2 WAMS PMC nodes in Gemalto, 10 WAMSP PMC nodes in Telecom Slovenije and 10WAMS PMC nodes in JSI have been provisioned with the FPAI XMPP software using ansible scripts and the FPAI management centre and are publishing data to the XMPP server. Additionally one SPM module has been provisioned with the FPAI XMPP software and publishes data to the XMPP server as well. The data of the Gemalto, TS and JSI WAMS PMC nodes are republished on an MQTT server so the respective partners can easily retrieve the information that is of interest to them. The information of the TNO WAMS PMC’s have been visualised in Grafana to show the power consumption and the power quality of a number of household appliances (refrigerator, coffee machine, television screens) and a number of computers used in the TNO lab and in a home environment as is shown in Figure 15.
3.4 WP5 - Field trial integration and validation

WP5 focuses on the planning, preparation and execution of the test polygon that will allow analysis of the strengths of the concepts and techniques developed in WP2, WP3 and WP4 in practice. The main goal of this WP is to physically setup, run and validate operation of large scale field trial. Deployment and validation of the use case scenarios is defined, and applications deployed and verified within.

First step in designing filed trial was selection of trial locations with testbed on manner to fulfil the base project aim of covering DSO and telco network. Preconditions for field trial location have to embrace as many possible existing and future communication network and cover all relevant SUNSEED use cases (Figure 16).
Figure 16: From classical operational approach towards advanced operation and control management approach in distribution grid (use case nm. 2)

Power network criteria (DSO responsibility):
- The locations have to cover at least one middle voltage supply feeder from main substation with all belonging secondary substations and their low voltage networks to the end consumer or prosumer.
- Beside traditional consumers the MV/LV feeders have to supply also prosumers and DER.
- Different types of DER (photovoltaics, small hydro, wind and cogeneration).
- Locations have to cover the urban and rural regions.

Communication network criteria (telco and DSO responsibility):
- Different types of current DSO communication infrastructure (fibre, PLC).
- Telco provide missing fibre, wire (xDSL) or mobile communication infrastructure (at least 3G or higher generation).

All these demands are covered in selected field trial locations Kromberk, Bonifika, Razdrto and Kneža. The locations Razdrto and Kneža are rural with high penetration of DER which creates high operational difficulties due to high voltage volatility. The Kromberk (part of city Nova Gorica) is attractive urban location.
near Elektro Primorska registered office needed for further upgrading smart grid project demonstration. Bonifika is part of city Koper and is very interesting location due to presence of optic fiber in DSO property.

On all locations comprehensive power and communication network coverage analyses were done. Due to additional needs of real time sensors in the network (WAMS nodes with PMU devices) the operational measurements are moving deeper alongside the low voltage all the way to end prosumers where utility currently does not dispose the proper communication network. The cooperation with telco operators with sustainable network infrastructure coverage (cellular: LTE; wireline: fibre, xDSL; wireless: RF mesh; PLC) is therefore essential. Therefore on all locations comprehensive power and communication network coverage analyses were done. Example of such analyses is shown in Figure 17.

![Figure 17: LTE radio coverage from base stations for field trial location Kromberk](image)

At the beginning we describe sources of data from field trial and data transport solutions. Smart meters are connected through PLC concentrators and deliver pseudo measurements for use in state estimation calculations. Interconnection of PLC concentrator to communication uplink is either through cellular LTE connection of fixed network utilizing build in Ethernet port. A general industrial grade LTE modem/router is used on field trial that can connect also to fixed network or WiFi via build in Ethernet L2 switch and wireless access point, respectively. WAMS node itself is a dual of measurement and communication device, crucial for voltage phasor measurements in distribution smart grid. Here we focus only on WAMS-SPM model, that supplies phasor measurements, whereas WAMS-PMC is used in laboratories for demand response like tasks.
At this stage the preliminary communication solutions were prepared on the available state of the art communication hardware data from smart meter technical catalogues, WAMS-SPM specifications and other supporting communication equipment. Important role in decision making belongs to first communication lab tests and live measurements on field trial locations. For end node installation the installation plan were prepared separately for smart meters with PLC data concentrators and WAMS-SPM units.

With smart meters installations we started immediately after delivery of them in Elektro Primorska’s warehouse (at M21). These installations perform special skilled workers from Elektro Primorska in parallel on all four trial locations. For WAMS SPM devices we started with pre-installations\(^1\) at M26. Final installations with all needed equipment we implemented at M33 after first WAMS SPM pieces delivery and continue gradually till M38. Smart meters with PLC data concentrators are installed on all locations according installation plans from D5.1.2 an updated version in D3.3.2. On the other hand total installations of WAMS devices slightly deviate from them, especially in location Kneža and Bonifika. In total we have installed of 38 pieces of WAMS SPM devices on 30 different geographical locations and 781 of residential smart meters with 24 PLC data concentrators. On field trial we also have of 97 industrial smart meters which were installed before SUNSEED project has started.

In SUNSEED field trial install the following equipment:

- **Measurements:**
  - Voltage phasor measurement units - PMU (WAMS-SPM device) – for measurement in distribution grid.
  - Smart meters – for pseudo measurements supporting state estimation and load forecasting.

- **Measurements synchronization:**
  - GPS antenna with supporting equipment.

- **Communications for measurements:**
  - LTE/UMTS routers,
  - Satellite modems/routers with supporting equipment,
  - Data concentrator for PLC communications to residential smart meters

All those equipment were connected to different communications scenarios. In summary, we distinguish two communication scenarios, where WAMS (SPM/PMC) nodes are connected through mobile or fixed modem/router (Scenario A) and WAMS SPM are using satellite modem/router (Scenario B). Scenario A is further divided into three sub-scenarios, where gateway (modem/router) could connect the LTE network (scenario A.1), UMTS network (scenario A.2) or xDSL/FTTH network (scenario A.3). Smart meters use mobile or fixed modems/routers as gateways via mobile or fixed network. However, with regard to the exact smart

\(^1\) Pre-installation means installation of all needed equipment at one site without WAMS SPM device.
meter model, they are connected to such gateways in different manner. We distinct two scenarios, where smart meters are connected to PLC data concentrator (DC), which is connected to mobile or fixed modem/router (Scenario C) or they are connected to mobile or fixed modem/router via RS485 to Ethernet converter (Scenario D).

Communication on field trial was completely implemented an all locations regarding communications scenarios designed in project. Most often (location Kromber - picture Figure 19 and Razdrto) the mobile communication network solutions by scenario A were used. On one specific locations in Kromberk, we decided to use the infrastructure of Elektro Primorska, who already has its mobile infrastructure for reading values of smart meters and aggregate it on location in Nova Gorica. In field trial location Kneža we solved communication for WAMS and SM connection with both scenarios, A and B. Scenario A1 was implemented in TS Sela nad Podmelcem with proper strength of LTE signal. In TS Knežke Ravne was the only possibility is satellite communication by scenario B (Figure 21). Field trial location Razdrto is connected through mobile communication network by scenario A1 and A2 and location Kromberk just with scenario A1. For all WAMS SPM devices connected in main supply substations and switching station Razdrto we use existing Elektro Primorska MPLS communication infrastructure on fiber physical layer (scenario A3).

Figure 19: Example of installation by scenario A1 in location Kromber, TS Pikolud (WAMS SPM and Teltronika modem/router in power box, data concentrator and GPS antenna for synchronisation.  

All the data from trial goes through Telekom Slovenije communication network with special developed SUNSEED architecture shown on Figure 20.
Figure 20: Telekom Slovenije Network for SUNSEED Trial.

Figure 21: Device installations example by scenario B in TS Knežke ravne vas where satellite communication was used.
All measurements from the field trial are accessible and visible on GIS portal called SunGIS (Figure 22). The basic role of the sunGIS application in SUNSEED project is to provide spatial information and orientation using general geographic and cartographic layers and information about the energy and telecommunication infrastructure using spatial data layers from TS, EP and SUNSEED (SM and WAMS nodes).

On field trial which consists of four different locations 819 of communication nodes were set up. 781 of them being smart meters and 38 WAMS SPM used for synchronized real time voltage phasors measurements. Some deviations regarding first installation plans occur due to several unpredictable technical and non-technical reasons like adoption of developed solutions needs, foreign ownership of secondary substations and equipment, no load or very small load presence on supplying 20/0,4 kV transformer, etc.. On the other hand some additional installations were made to demonstrate usefulness of WAMS SPM for detecting phase sequence detection between neighbourhoods main supply substations in case of reserve supply restoration.

In parallel with installation set up we focusing also on validation of field trial. The validation was made for physical installations on field trial, communication network with developed communication solutions and for power measurements as inputs for developed applications.

Regarding communication network performance, we have analysed the latency performance (by measuring the RTT) of the SUNSEED smart grid communication network and briefly looked at the one-way delay of the WAMS-SPM power measurement data. The communication network that was used is primarily LTE and in some locations, alternative solutions such as UMTS, Fiber, and satellite communication. At the application layer, a lightweight M2M messaging protocol called MQTT has been used in conjunction with RabbitMQ, a messaging broker software. We found out that fibre has the best latency performance (i.e. lowest RTT) followed by LTE, UMTS and satellite, which conforms to the general expectation. The measured latency performance of LTE (mean RTT between 20 -50 ms) conforms with the user-plane RTT values from existing studies and field trial results in the literature.
Traffic flow analyses have shown that the traffic flow of WAMS-SPM devices depends highly on the type of network connection. While all devices transmit 50 power measurements per second, the TCP and RabbitMQ protocols used adapt to the link properties and conditions, which affects the number of IP packets being transmitted and their sizes. Fiber uses many small packets, whereas LTE and UMTS send larger amounts of data per packet.

Regarding power measurements validation we are focusing to those measurements, which will enable the full observability and forecasting of the distribution system, either as an input measurement in the distribution system state estimation, or as an independent measurements serving as an input into forecasting modules or just for presentation in the visualisation software. Evaluation of the distribution system state estimation (DSSE) was done on one field trial location. Validation analyse shows that magnitude error is smaller than 0.2 % and phase error is below 0.01 degrees. Prediction evaluation shows that regression models work only slightly better than moving average models at very short and at longer prediction horizon.

In the project we establish robust communication network to connect power measurements with developed applications to ensure observability of voltages and power flows for more efficient operation of distribution grid. However, final step in WP 5 was evaluation of all solutions and results for converged DSO-telecom communication network supporting future smart grids. In D5.4 we collect all recommendations for installation, communication and power measurements application solutions obtained in research and practise work done in whole project.

Figure 23: Common smart grid architecture and positioning of project SUNSEED within it.
To conclude, we could found out that in SUNSEED we establish connection (communication and information layer) between power measurements (component layer) with developed applications (function layer) to ensure observability of voltages and power flows for more efficient operation of distribution grid. Finally we also analysed different business models between power, communication and regulatory stakeholders and propose optimal one. This means, we actually covered almost all layers in common smart grid architecture shown on Figure 23.
4 The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

4.1 Potential impact

The EU’s renewable energy directive specifies a target of 20% energy generation from renewable sources by 2020. Many EU countries are already committed to reach their national targets and renewable generation is across Europe is on the increase. National plans include different mix of renewables addressing several sectors including electricity, heating, cooling and transport. The revised renewable energy directive in 2016 increases this target even higher.

Increase in renewable generation and low carbon loads create new dynamics in the traditional electrical distribution networks. The challenges faced by distribution network operators are both technical and non-technical and varies from country to country. For instance, in certain parts, networks are constrained that connecting new renewables requires huge capital investments for reinforcing the connections while on other networks unpredictability and variability of renewable generation create operational challenges.

SUNSEED project partially tries to address the challenges to do with wider renewable and low carbon deployments. In particular, SUNSEED developed and trialled a relatively low cost solution to provide increased observability at distribution networks. Increased observability is the first step towards developing a smart distribution grid to assist in meeting low carbon targets.

Based on the technology and trial know how following key outcomes has been achieved:

- Project has shown that existing communication technologies are capable of meeting the near real-time requirements of distribution grid operation and optimisation algorithms.
- Project has demonstrated how telecom operator network could play a key role in assisting distribution network operator creating innovating market models.
- Project has proposed a set of business models for the smart distribution grid based on the coloration between the telecom operators and DSOs.
- Project has demonstrated that high quality power measurements, as the PMUs can provide, are able to achieve in the distribution grid using a low cost device.
- Project has demonstrated a data management security platform for an end-to-end publish-subscribed mechanism.
- Project has been collaborated with a number of EU funded research projects, such as FP7 ‘Advantage’ and ‘VIMSEN’, and H2020 ‘P2P-SmarTest’, in a number of scientific workshops and technology demonstrations.

Overall, the technology and market innovation of SUNSEED will not only benefit the telecom and distribution operators but also will assist wider communities who are willing to operate as prosumers of energy.
4.1 Main dissemination activities

Start of the SUNSEED project was publicised in 7 news publications and web sites. Slovenian main newspaper Delo covered it. There was a short press conference after the SUNSEED kick-off meeting.

The SUNSEED consortium has successfully organised 4 technical workshops, covering various topics within the scope of the project. The first workshop on Advanced Control, Communications and Algorithms for the Smart Grid, was held at Aalborg University in Denmark. The workshop attracted 53 registered participants to discuss the communications in smart grid, and the requirements to the communication from different sides. The second workshop on Smart Grid Observability and Control; Demonstrations and Trials for Real-Time Smart Grid Control was a very successful one-day event including a morning session oriented to the research community and an afternoon session focused on the industry parties. The workshop took place in TNO venue, The Hague, The Netherlands with 41 registered attendees mainly from industry and related EU research projects. The third workshop entitled “Where the Power Grid & Telecom Network” was organised within the much larger EU utility week 2016 exhibition in Barcelona, Spain. The exhibition was visited by 12.000 international visitors and over 600 exhibitors showcased their solutions across the entire smart energy value chain, from transmission to end-user. The workshop discusses the usage of existing telecommunication networks for future smart grids and provided the audience an overview of IoT technologies available from GSMA perspective. Altogether 64 visitors registered to attend the workshop. The forth workshop entitled “Smart Distribution Networks: Technologies and Business models”, was organised by SUNSEED in collaboration with H2020 project ‘P2P-SmarTest’ and FP7 ‘Advantage’. This workshop aims to present recent research findings and trial results from three projects and to discuss about disruptive technologies and business models for distribution networks. The workshop has 9 presentations, 2 panel sessions covering technology and business aspects in future smart distribution network, as well as a technology demonstration/exhibition session, where the three projects showcased their solutions across the smart distribution network. Based on the received feedback the 38 attendees were very satisfied with the workshop. The workshop was held in London on April 10 2017.

SUNSEED exhibited at Mobile World Congress (MWC) held in Barcelona in March 2015 under the sponsorship of the GSMA. At this event, SUNSEED showed an early prototype demonstrating its security and trust management solution for smart grid involving the use of an embedded secure element (an eUICC) in the device. Mobile World Congress is the largest world-wide event in mobile communications and has a huge media impact, with more than 90,000 visitors in 4 days. The prepared pitch was delivered to more than 300 visitors during the show. Our demo has been well received and attracted media coverage such as Electronics360.

In February 2016 GSMA published a case study based upon the SUNSEED project. This case study, primarily targeted at utilities companies is showcasing the problem addressed by the SUNSEED project and the benefits of the solution implemented in the project. It explains in particular how Telekom Slovenia has been integrated as a major player of the project to provide the SUNSEED communication network and ensure the security of SUNSEED communications. ([http://www.gsma.com/connectedliving/the-electricity-grid-of-the-future](http://www.gsma.com/connectedliving/the-electricity-grid-of-the-future))

The research of SUNSEED has led to a significant number of paper publications in top IEEE journals including the IEEE Wireless Communications Magazine, and IEEE Journal on Selected Areas in Communications, as well as conference proceedings such as the IEEE ICC, GLOBALCOM, ISGT, SmartGridComm, and Energycon. The SUNSEED project has been presented many times at conferences, academic seminars, public talks, and exhibitions by relevant members of the consortium. In every paper publication, the EU and the SUNSEED consortium are fully acknowledged. The detail of the publication activities can be found in Project deliverable D6.2.2.
During the project duration, SUNSEED has carried out dissemination activities in terms of technology standardisation, either ensuring the technologies developed are in line with the standards already in place or influenced the next generation of standards based on the SUNSEED experience. For example, efforts are being made in the standardisations consortiums for the new standards for IoT and 5G technologies to include specifications to accommodate wide-area monitoring systems for power distribution networks such as the one tested in the SUNSEED project. Project deliverable D6.3 summaries these activities.

4.2 Dissemination materials

A comprehensive Promotional Kit was produced which includes the active SUNSEED website, document templates and project banners (physical banner is available at TS premises and used at public events). Dissemination materials have also been produced individually for each of the aforementioned workshops. Project deliverable D6.1.2 describes the Promotional Kit.

4.3 Exploitation of results

Partners of the SUNSEED consortium have identified result exploitation opportunities within their relevant business sectors, determined the most promising exploitation routes for each exploitation opportunity (i.e. through standardisation or directly with product divisions) after the project has finished, as well as any barriers to exploitation (such as regulations etc.). For example, Elektro Primorska will fully exploit SUNSEED equipment, developed technology and services. The WAMS SPM node is seen as an indispensable measuring element in future distribution network as it is a basis for some advance services like unbalance state estimator, protection pattern recognition, phase detection. There have been activities on SunGIS platform marketing, the goal is to position it as a network monitoring support tool for DSOs, either as a solution deployed within DSO's infrastructure or as a service residing in TS's cloud infrastructure. TS's GIS solution have been also recognized as a platform candidate in recent activities within project of Slovenian smart specialization lead by Slovenian government. JSI was proceeding with presenting the foreseen/already implemented features of WAMS node to potential customers/investors. For this purpose, they presented the availabilities of WAMS and state estimation at workshop demonstrations and also at dedicated customers. JSI sees the exploitation of WASM in different directions, (i) as additional communication module using RS485/Ethernet connection to SM; (ii) standalone synchronized phasor measurement unit that would allow advanced power system monitoring in distribution grid or (iii) as integrated solution (i.e. WAMS node together with state estimation as a service). The real-time analytics and short-term generation/consumption forecasting module was also presented at workshop and to potential industry leading to further collaborations. In addition, the newly acquired knowledge and experience was/will be integrated in the education process at the Jozef Stefan International Postgraduate School, in particular in courses concerned with modelling and simulations in telecommunications, sensor technologies and wireless communications.
4.4 The address of the project public website and the relevant contact details

SUNSEED website: [www.sunseed-fp7.eu](http://www.sunseed-fp7.eu)

Table 1: List of relevant contact details

<table>
<thead>
<tr>
<th>Beneficiary name</th>
<th>Contact</th>
<th>Country</th>
<th>Website</th>
<th>Logo</th>
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</thead>
<tbody>
<tr>
<td>Telekom Slovenije</td>
<td>Peter Zidar, PhD</td>
<td>Slovenia</td>
<td><a href="http://www.telekom.si/en">http://www.telekom.si/en</a></td>
<td><a href="http://www.telekom.si/en">Telekom Slovenije</a></td>
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<tr>
<td>Aalborg University</td>
<td>Jimmy Nielsen</td>
<td>Denmark</td>
<td><a href="http://www.aau.dk/">http://www.aau.dk/</a></td>
<td><a href="http://www.aau.dk/">Aalborg University</a></td>
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<tr>
<td>Jožef Stefan Institute</td>
<td>Aleš Švigelj, PhD</td>
<td>Slovenia</td>
<td><a href="https://www.ijs.si/">https://www.ijs.si/</a></td>
<td><a href="https://www.ijs.si/">Jožef Stefan Institute</a></td>
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</table>
5 USE AND DISSEMINATION OF FOREGROUND

Section A (public)

This section includes two lists

- List of all scientific (peer reviewed) publications relating to the foreground of the project.

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project. Updates are possible at any time.
<table>
<thead>
<tr>
<th>NO.</th>
<th>Title</th>
<th>Main author</th>
<th>Title of the periodical or the series</th>
<th>Number, date or frequency</th>
<th>Publisher</th>
<th>Place of publication</th>
<th>Year of publication</th>
<th>Relevant pages</th>
<th>Permanent identifiers² (if available)</th>
<th>Is/Will open access³ provided to this publication?</th>
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<tr>
<td>4</td>
<td>A Mean Field Game Theoretic Approach to Electric Vehicles Charging</td>
<td>Ziming Zhu</td>
<td>IEEE Access</td>
<td>Volume: 4</td>
<td>IEEE</td>
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<td>2016</td>
<td>3501 - 3510</td>
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<td>5</td>
<td>Estimation of Received Signal Strength Distribution</td>
<td>Mathias Rønholt</td>
<td>IEEE Wireless Communications</td>
<td>Volume: 6, Issue: 1</td>
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² A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

³ Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.
<table>
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<tr>
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<th>Place</th>
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<th>Size of audience</th>
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<tr>
<td>1</td>
<td>Conference</td>
<td>German Corrales Madueño</td>
<td>Efficient LTE Access with Collision Resolution for Massive M2M Communications</td>
<td>December 2014</td>
<td>IEEE GLOBECOM, Texas, USA</td>
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<td>2</td>
<td>Conference</td>
<td>Čedomir Stefanović</td>
<td>SUNSEED – an evolutionary path to smart grid comms over converged telco and</td>
<td>May 2014</td>
<td>Global Wireless Summit 2014, Aalborg, Denmark</td>
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4 A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

5 A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other (‘multiple choices’ is possible).
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<tr>
<th>Conference</th>
<th>Participants</th>
<th>Title</th>
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<td>4</td>
<td>Conference</td>
<td>LTE Delay Assessment for Real-Time Management of Future Smart Grids</td>
<td>February 2016</td>
<td>1st EAI International Conference on Smart Grid Inspired Future Technologies, Liverpool, UK</td>
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<td>A Tractable Model of the LTE Access Reservation Procedure for Machine-Type Communications</td>
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<td>Short term forecast of wind power generation based on SVM with pattern matching</td>
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<td>Conference</td>
<td>Low-voltage-grid state estimation testbed</td>
<td>September 2015</td>
<td>IEEE 24th International Electrotechnical and Computer Science Conference ERK, Portorož, Slovenia</td>
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<td>10</td>
<td>Conference</td>
<td>A Unified Three-Phase Branch Model for Distribution System State Estimation</td>
<td>October 2016</td>
<td>IEEE ISGT EUROPE 2016, Ljubljana, Slovenia</td>
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<td>11</td>
<td>Workshop</td>
<td>Advanced Control, Communications and</td>
<td>March 2015</td>
<td>1st SUNSEED workshop, Aalborg, Denmark</td>
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<td>Workshop</td>
<td>Ljupčo Jorgušeski</td>
<td>Smart Grid Observability and Control; Demonstrations and Trials for Real-Time Smart Grid Control</td>
<td>March 2016</td>
<td>2nd SUNSEED workshop, The Hague, The Netherlands</td>
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<td>13</td>
<td>Workshop</td>
<td>Peter Zidar</td>
<td>Where the Power Grid &amp; Telecom Network Meet</td>
<td>November 2016</td>
<td>3rd SUNSEED workshop in European Utility Week</td>
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<td>Mahesh Sooriyabandara</td>
<td>Smart Distribution Networks: Technologies and Business models</td>
<td>April 2017</td>
<td>4th SUNSEED workshop, London, UK</td>
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<td>16</td>
<td>Workshop</td>
<td>Radovan Sernec</td>
<td>PLC and LTE interconnect for state estimation in distribution grids</td>
<td>September 2015</td>
<td>9th Workshop on Power Line Communications WSPLC 15, Klagenfurt, Germany</td>
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<td>18</td>
<td>Workshop</td>
<td>Ljupčo Jorgušeski</td>
<td>SUNSEED overview</td>
<td>January 2015</td>
<td>Workshop on independent networks, NYU, USA</td>
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<td>19</td>
<td>Presentation</td>
<td>Peter Zidar</td>
<td>Mobile operators and 5G • EU Smart Grid projects • IoT in LTE and 5G networks</td>
<td>October 2016</td>
<td>Telco Data Analytics &amp; Location Based Services Europe, Madrid, Spain</td>
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SUNSEED Project final report, Grant agreement No. 619437
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<tr>
<td>20</td>
<td>Presentation</td>
<td>Peter Zidar</td>
<td>Project SUNSEED: Establishing role of telecoms in future smart-grids</td>
<td>April 2017</td>
<td>10th Annual Telecoms Energy Efficiency Forum, Barcelona, Spain</td>
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<td>21</td>
<td>Presentation</td>
<td>Hervé Ganem</td>
<td>IOT and security</td>
<td>February 2015</td>
<td>Public round table at GSMA</td>
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<td>Presentation</td>
<td>Hervé Ganem</td>
<td>A basic secure element for IOT</td>
<td>March 2015</td>
<td>Global platform workshop</td>
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<td>23</td>
<td>Presentation</td>
<td>Hervé Ganem</td>
<td>Distributed security architecture for IOT</td>
<td>June 2015</td>
<td>ETSI security week</td>
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<td>Distributed security architecture for IOT</td>
<td>June 2015</td>
<td>Working session of ESMIG group</td>
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<td>25</td>
<td>Presentation</td>
<td>Hervé Ganem</td>
<td>Outsourcing IOT security management</td>
<td>September 2015</td>
<td>World smart week conference</td>
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<td>26</td>
<td>Presentation</td>
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<td>IOT security overview in Paris Sept. 2015</td>
<td>September 2015</td>
<td>Conference organized by ‘pole systematic’ ,Paris, France</td>
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