Final report

1.1 Project details

Project title	REliable MOniToring and Estimation of distribution GRID for smart societies
Project identification (program abbrev. and file)	ForskEl (EUPD)
Name of the programme which has funded the project	Energistyrelsen
Project managing company/institution (name and address)	Aalborg Universitet, Department of Electronic systems Fredrik Bajers Vej 7, 9220 Aalborg Ø
Project partners	Aalborg Universitet, Kamstrup and Thy-Mors Energi
CVR (central business register)	29102384
Date for submission	28th February 2020 (Postponed to April 17, 2020

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1.2 Short description of project objective and results

English Version

Objectives: The objective of this project is to enable DSO's to obtain a cost effective flexible, comprehensive and reliable visualized overview of their low voltage grid for near-real time operations and long time scale planning.

Results: the project developed a visualization tool based on a database management system, that allows simple and effective interactive overview of measurements in the low voltage grid, useful for asset management. This tool is supported by different research results on data access networks, big data and grid state estimation, that jointly improves the quality of the visualization tool. Finally, the project developed a set of simulation and training tools to allow tests and training of personnel in failure and cyber-attack situation.

Danish Version

Objectives: Dette projekt fokuserer på at udvikle et system til DSO'er med formål at opsamle, visualisere og anvende data fra smart meters i lavspændingsnet, og evaluere dette system i 1) en test bed med fokus på validering og analyses af fejlsituationer og cyber-attacks, og 2) en field test med fokus på visualisering og operationel anvendelse af data.

Resultater: Projektet har udviklet en visualiseringsplatform til visning af målinger i lavspændingsnet, der tillader DSO'er let adgang til at få indsigt i hvordan deres grid opererer og finder anvendelse til asset management. Dette værktøj er understøttet af flere forskningsresultater indenfor data acces management, big data og tilstandsestimering af grid, der alle bidrager til forbedringer indenfor visualiseringsværktøjet. Endelig har projektet udviklet simuleringsmodeller og træningsværktøjer til tests og træning af folk.

1.3 Executive summary

The RemoteGRID project has been divided into several phases: 1) an *analysis phase* where the consortium has been focused on identification of specific problems that the project would work on. Two cases has been selected among a larger set of cases, namely *Improved low-voltage grid observability* and *Asset Management*. These has been documented in [D1.1] and [D1.2]. These two deliverables later led to requirements and an architecture, documented in [D1.3], which served as a guidelines for the technical work in the project. 2) a *research and development phase*, where main research on data access networks, database and data processing, and state estimation has been carried out. 3) an *integration phase*, where components has been integrated in laboratory as well as field test, and 4) an *assessment phase*, where the DSO has been given opportunity to work with the tool and gain some day-to-day experience with the tool. This was the plan, and has been roughly executed as described. However, during the project, some timing issues happened for various reason, which has caused some minor changes in prioritization, but these did not change the major outcome of the project.

The results from the field tests has been very promising, and has shown significant impact on the way Thy/Mors Energi carries out their daily work. In addition to the tool, the close collaboration between Aalborg University and TME has been of great benefit for both parties, and will continue long after this project ends. Kamstrup has gained lots of knowledge on use of smart meter data for next generation smart meters, and similarly the close collaboration between AAU and Kamstrup has been fruitful for both parties, and will continue long after this project. The laboratory setup with specialized tools, that is the second main technical outcome of the project, is expected also to be used in other project, but also for training and educational purpose.

1.4 Project objectives

In this section we briefly introduce the project objectives and the implementation of the project. We provide an overview of the project structure and how the resources were planned and used.

Motivation and background

Initially, the procedure of how a DSO as TME would inspect their low voltage grid, has been cumbersome and filled with several manual steps involving use of several separate applications and required interaction with different centres. The technical flow has been illustrated in Figure 1.

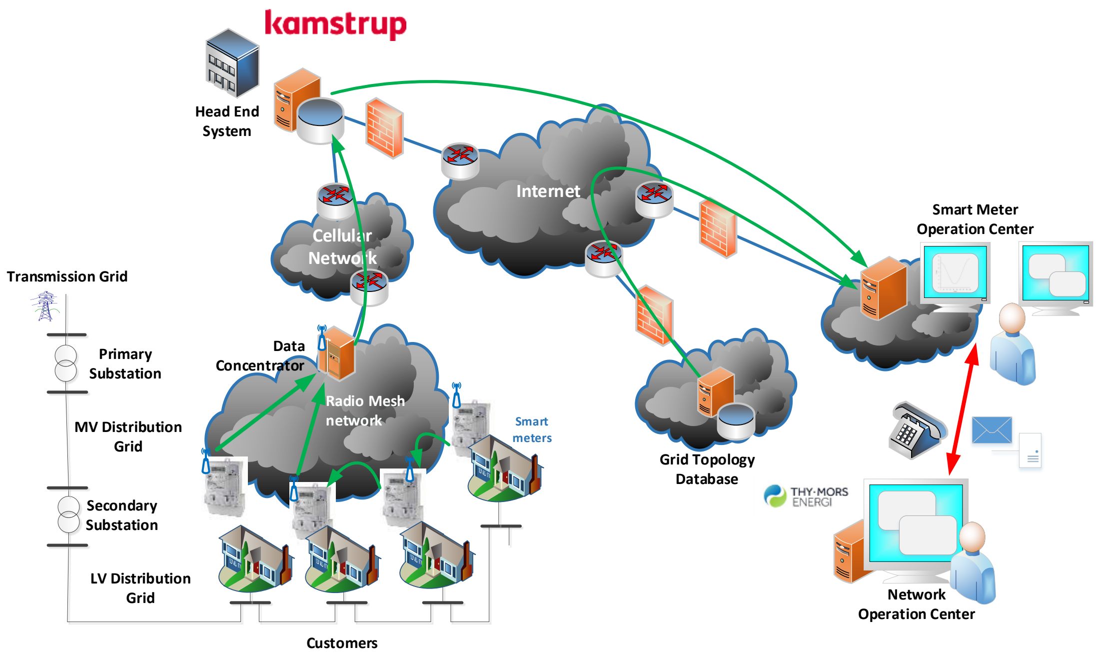

Figure 1: Overview of pre-existing system before RemoteGRID

To the left, data is measured by Kamstrup via a radio mesh network, and data is pushed to the HES. If TME would do any investigations of their grid for e.g. fault localization, they would need to apply several applications that are located in two places, the Network Operation Center (NOC) and the Smart Meter Operation Center (SMOC) which are not physically co-located, and requires communication over email and phone-calls. To make work processes even more complicated, grid topology data is stored in a separate database as well as other files. Hence, the process for locating errors and faults in the low voltage grid, is often very time consuming. The RemoteGRID project's main objective is to reduce the work flow needed for carrying out such operations as well as management of assets, under the constraints that the AMI is low capacity and data quality is timely affected badly in the collection process.

Problem objectives

The overall objective of the project as described in the project application is to *enable energy system managers to obtain a cost effective flexible, comprehensive and reliable visualized overview of their energy systems for near-real time operations and planning*. The central element of the project is data quality which is a qualitative metric that is affected by many elements in the process from measurement to visual presentation to the system operator. In RemoteGRID we focused on three sub problems: data management & processing, data collection and state estimation, that jointly and in interaction should provide relevant and timely information about the grid state. In addition, the project application targeted to investigate use of data from smart meters for asset management.

The method of approach to this objective has been twofold: develop and implement a field test that allows testing of the concept under true conditions, and development and test of a lab setup with models for validation and test of cases that cannot be tested in real life, e.g. failures.

The outcomes of the project have been targeted to benefit DSO's in their daily operation and planning of their low voltage grid. Secondarily, metering companies like Kamstrup to understand requirements for next generation smart meters and for universities as AAU to focus research on real world problem and bring research into the industry for societal and industrial benefit.

In the end of the Project the following objectives were achieved:

- Implementation and testing of a Visualization Tool based on measurements from Smart Meters for monitoring
    - Field test setup and daily use validation
    - Lab setup and validation of concept
- Scientific contributions for
    - Smart and adaptive data quality aware collection
    - Smart visualization of large data
    - Real time grid and asset management functionalities
- Security threat and impact analysis of cyber-attacks on systems relying on smart meter measurements
- Analysis and alignment with the current legislations on handling smart meter data

Project organization and implementation

This objective has been broken into several sub objectives, that has driven the work packages in the project. Three technical work packages (WP2-WP4) has been dedicated to each technical aspect of the project, supported by WP1 which purpose has been to provide an architecture and framework that the three work packages could operate within. The structure is shown in Figure 2, and objectives from the project application summarized below.

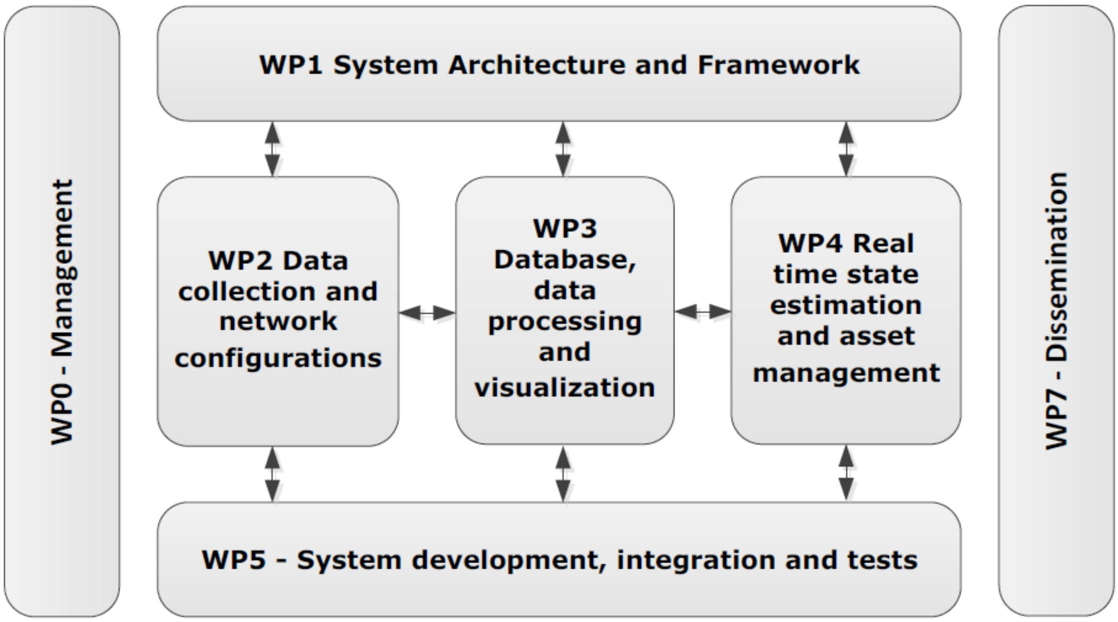

Figure 2: Project structure in work packages

WP1 – System Architecture and Framework:
Objectives: *Use cases and KPI definitions, system requirement definitions, threat analysis and security assessment, recommendations to regulatory frameworks.*

WP2 – Secure Data Collection and Network Configurations:
Objectives: *Efficient and secure methods for aggregation of data, secure adaptive scheduling mechanisms for data collections, planning methodologies for secure realtime network configuration and adaptation, efficient algorithms to use third party networks for reliable data provisioning*.

WP3 Database, data processing and visualization:
Objectives: *provide the technical solution of a data collection, processing and visualization mechanism*.

WP4 – Real time state estimation and asset management
Objectives: *Low complexity algorithms for real-time state estimation, simple and accurate consumer prediction models, methods and algorithms for asset management.*

WP5 – System development, integration and tests
Objectives: *test and verify developed functionalities in WP2, WP3 and WP4.*

The work effort has been distributed across all work packages. As mentioned in the original application, far the largest part of the budget have been spend on salary, which is demonstrated in the below table. In Figure 1, the effort should be seen in relation to the total budget and the % show how the effort is divided between all the work packages.

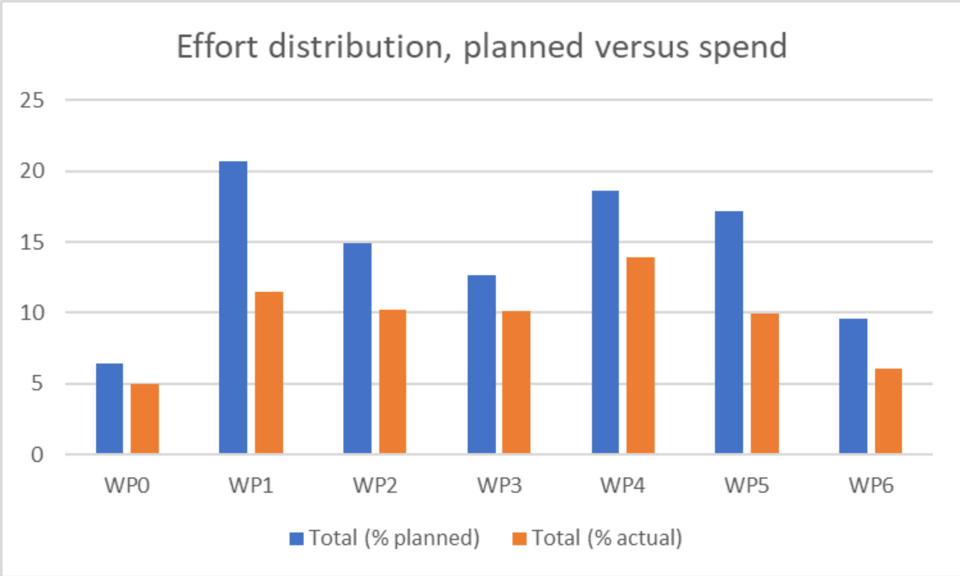

Figure 3: Overview of work package effort in percentages relative to the total budget for the project period and the actual spend resources.

WP0 is the management work package and took the least share of the budget. WP1 has spent the largest part of the budget, with more than 20% of the total effort, followed by the technical work packages 2-5. Figure 4 shows the planned distributed work in the project among partners per work packages.

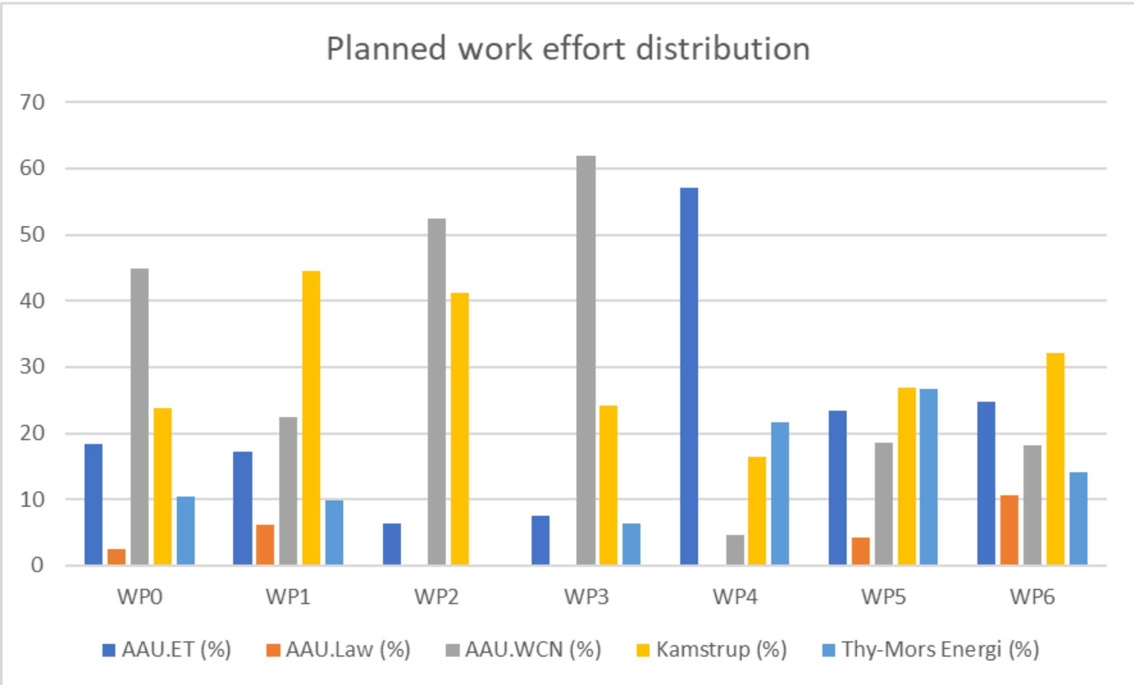

Figure 4: Distribution of effort per partner in percentages relative to the planned effort in each work package

A couple of notes to this distribution is that for AAU-WCN has significant amount of leadership and effort is caused by this section covering two of the three main topics in the project, i.e. WP2 and WP3. The third main topic is covered by AAU-ET, hereby making AAU main responsible for the technical work packages wherein all research has been ongoing. The industrial partners, has been driving WP1 on the use cases and system architecture

(Kamstrup), a natural choice for their role to drive the framework of the WP2, WP3 and WP4. For WP5 the natural choice has been Thy-Mors Energy as they 1) hosts the field test site and 2) are the main take of the project outcome, so with them driving the KPI definitions and overall assessment framework, they naturally has lead this work package. For dissemination activities, while the leadership officially has been Kamstrup, all has in reality participated as best possible and collaborated closely on the disseminations at both national as well as international events.

Project limitations and choices

Several adaptions and changes has been mad during the project period, to adapt to the lessons learned and shape the focus with the given resources. In this section a brief overview of the most major ones are given.

- The size of the field test was originally planned to be much larger. A list of criteria for site selection was made early in the project. These criteria were taking into account e.g. distance from TME Head Quarter, deployment of AMI, mix and share of customers and renewables, existing power/voltage quality challenges, etc. An assessment of several potential candidates on TME premises pointed out that few locations were actually meeting the evaluation criteria. Therefore, the selected location is having a smaller size but on the other hand fulfil all the other criteria. Moreover, the selected location presents advantages for practical reasons related to the validation and testing part i.e. GIS mapping, retrieving of grid parameters and topology, realization of a Real-Time model in laboratory, etc..
- The inclusion of user activity study was originally not planned in the project, but was embedded into the project along the way to gain insight into the impact of developed tools in everyday work of the DSO operators. This inclusion has provided much valuable insights into the use of this system and it is one of the main outcome of the project.
- The deployment of the backend server system in a cloud environment, was not originally planned, but the decision to do this, heavily simplified the integration of the AMI and backend system compared to the initial planned solution.

Project evolution

Table 1 provides an overview of the deliverables that has been produced throughout the project period. The most ones are produced by the technical work packages 2, 3 and 4 and contains the details of the research results obtained in the project as well as models. Later in this report, there will be an overview of the main findings based on these deliverables.

Del. No.	Deliverable title	Issuer	Date	Length
[D0.1]	Quality ensurance plan	AAU	June 2016	16p
[D1.1]	Use cases, architecture and framework	Kamstrup	Feb. 2017	15p
[D1.2]	Final requirement specifications	Kamstrup	April 2018	20p
[D1.3]	Final system architecture specifications	AAU	Jan. 2019	25p
[D2.1]	Data collection framework and aggregation and data modelling	AAU	Feb. 2018	48p
[D2.2]	Threat mitigation mechanisms	AAU	June 2019	28p
[D2.3]/ [D4.2]	Data access and state estimation interaction	AAU	July 2019	33p
[D3.1]	Data base system specifications and requirements	AAU	April 2017	28p
[D3.2]	Low complexity processing and feature extraction techniques	AAU	Oct. 2018	25p
[D3.3]	Visualization module documentation	AAU	Dec. 2019	29p
[D4.1]	Implementation description of power distribution grid	AAU	March 2018	22p
[D4.2]/ [D2.3]	Data access and state estimation interaction	AAU	July 2019	33p
[D4.3]	Advanced Observability and Asset Management of Distribution Grids	AAU	Feb. 2020	50p
[D5.1]	Assessment framework and KPI specifications	TME	Dec. 2019	25p
[D5.2]	Final system test and assessment report	TME/AAU	Feb. 2020	36p
D6.1	Mid-term dissemination assessment plan	Kamstrup	May 2018	16p
D6.2/ D6.3	Final dissemination and exploitation plan	AAU/ Kamstrup	Jan. 2020	17p
[Hendrup19]	GDPR analysis report	AAU	Sept. 2019	42p

Table 1: Overview of deliverables produced throughout the project

Some additional reports, not planned originally, has been made, e.g. [D0.1] which includes guidelines to the involved people on how to work with data from TME. This document was elaborated to ensure a transparent set of rules and clear guidance for handling the data related to test site. Moreover, this documents ensured that no conflicts with GDPR rules may arise during the project and beyond. Later in the project, a dedicated technical note has been elaborated as to analyse the GDPR rules, [Hendrup19]. Besides, this architecture and framework has been captured in deliverables from WP1 and results obtained in the two key deliverables [D5.1] and [D5.2], respectively.

Finance

On overall level the RemoteGRID project succeeded to deliver on all the planned objectives and produced some very interesting results. The actual spending of the effort is shown in Figure 5 in percentages relative to the planned budget per partner.

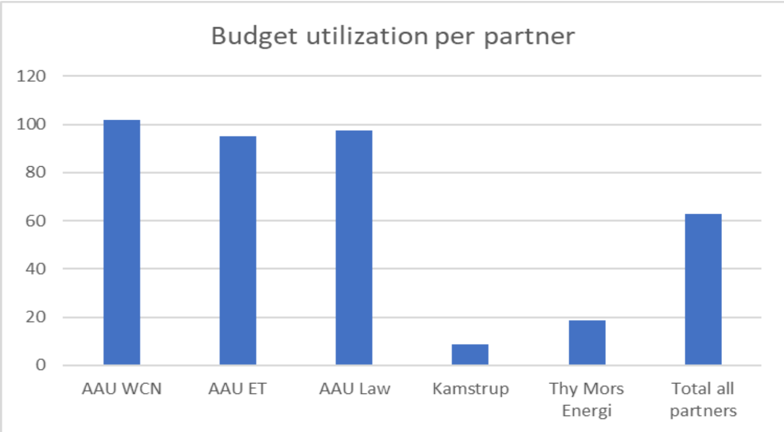

Figure 5: Resource utilization per partner relative to the planned budget. The numbers includes reasonable estimates for the last period.

It is clear here that the industrial partners have significantly under spend according to the plan. There are several explanations to this is fact, and the key has been a change of focus in the field test. At the project planning phase, a large focus was on the real-time aspect of visualizing data from a larger area, which would require significant effort from Kamstrup. However, during the project, it became clear that the real-time aspect in the field test were not as critical as initially expected. Scope was shifting more towards showing the right data at the right moment, and not showing all data in real-time. This shift of focus has reduced complex operation needed at Kamstrup site, as cost versus gain simply did not justify the originally intended technical direction. Hence, a reduced resource demanding and yet more efficient solution was adapted, leading to a much less effort consumption. Another part of this decision was the situation of GDPR enforcement rules which were came in act in 2018. This enactment lead the consortium to shift some aspect from the field test into the laboratory to avoid potential legal issues before these were settled. These aspects were finally solved in the late part of the project, but at that time, the project had already been extended by 6 months and it was concluded that due to the digital twin solution, no further extension nor expansion in the field test site would bring significant contributions as further value would be in failure and attack scenarios which anyway are only feasible to demonstrate in the digital twin. Hence, the work has been pushed, as also visible towards the university. Further, a part of the field study with Thy-Mors Energy was later carried out by students in problem based learning settings, were some findings hence were free. Similar such studies involving students have been done in work package 2 – 4, and the use of paid student helpers in the project have also lead to reduced effort as compared to the planned effort. Further, various conditions in partners during the project period, have also impacted the resource spending of partners. Finally, the project have also been benefiting from collaboration with other projects where all three partners have been involved in.

In any case, despite the underspending, the project ended with a successful implemented demonstration system in the field, a digital twin and assessment of the system concept as planned.

Project results and dissemination of results

For the final setup in RemoteGRID the consortium has established a backend system consisting of interface components, database, and adapters, that acts as the interfacing link between Kamstrup's HES and alarm interface, to the front end which essentially is the GUI available in NOC for daily operation. Thus the classical communication channels between NOC and SMOC, as shown in Figure 1 is no longer needed, and NOC operator are now being able to check on-line status of the low voltage grid by accessing Smart Meter data. The links and procedures are shown in Figure 6, which shows the overall information flow from Kamstrup to the RemoteGRID backend from where access to the front end is done directly from the intermediate database.

This architecture creates the background for the assessment carried out in this report. The basis for assessment are the use cases which focuses on grid monitoring and asset management.

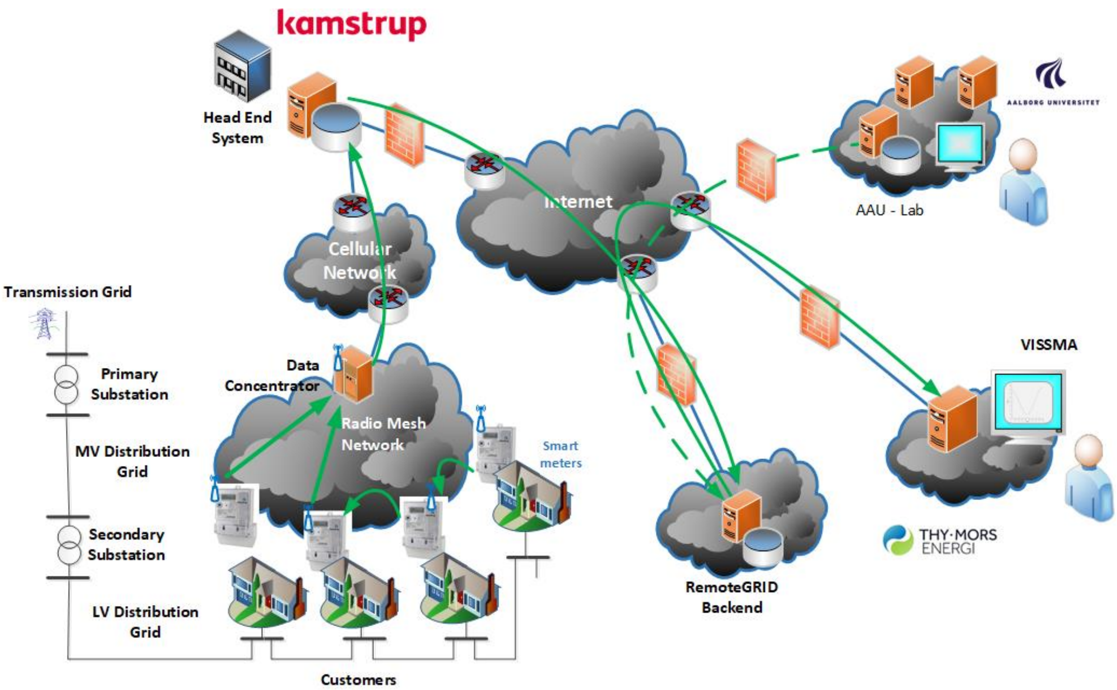

Figure 6: After RemoteGRID access to smart meter data has been simplified, by inserting a RemoteGRID backend service, which also allows interaction with AAU Lab generated scenario traces for training purposes.

The main differences from the start of the project is the single integrated GIS application, deployed at the DSO premises, can connect to all data sources and show measurements in a context, i.e. an integrated GIS system. The overall process flow is now such that while data is still being measured and collected by Kamstrup using its infrastructure, data is pushed to the RemoteGRID database, from where it is being accessed by the GUI (which we named VISSMA). The downstream information from the RemoteGRID backend is available to a client who has a browser and access (VPN) to the cloud, meaning that both NOC and SMOC can have easily access to the same information

1.4.1 Work package 1: System architecture

From work package one and five the system architecture and system components has been defined and put into a system context, as shown in Figure 7. The figure shows the end result of the refined architecture described in [D1.3] and maps the components developed from WP2, WP3 and WP4 into a WP5 context using the SGAM framework, [CENELEC12].

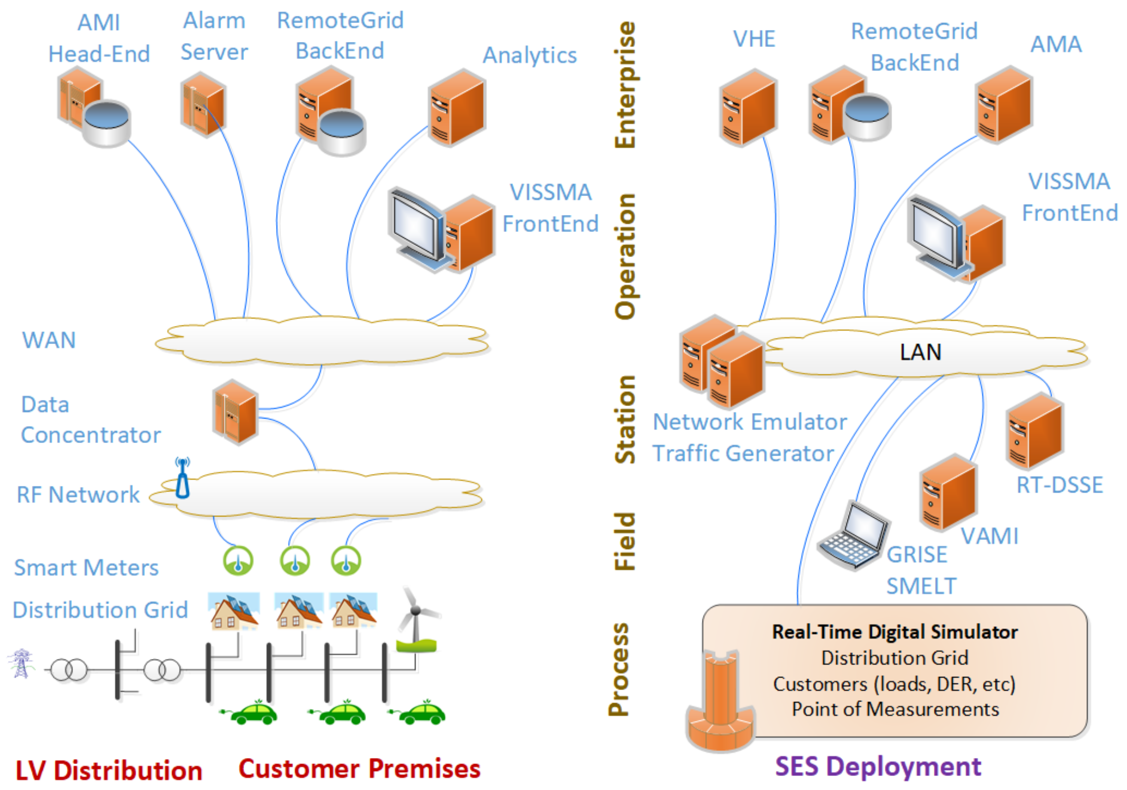

Figure 7: Final system architecture of field test and lab mapped to SGAM

To the left in the figure, the various components in the field are shown, along with the pre-existing AMI, as described in [D5.2]:

- RemoteGRID Backend services: which includes the database, interface software to the Kamstrup's HES and web service to serve the visualization front end. See [D3.3].
- Analytics: service that performs the state estimation and asset management functionality. See [D4.3].
- VISSMA frontend: the client part of the visualization system that allows the operators to properly view data from the RemoteGRID backend. See [D4.3].

The flow of information is such that data related to the electrical grid at process level, is firstly collected via the AMI in the field by a set of concentrators, that ensures data is collected and pushed to the head end system. The AMI relies on a reliable, but low capacity and low data rate radio mesh network, and concentrators relies on other types of networks such as cellular or fiber connections to the HES. Data is thereafter pulled by the RemoteGRID backend system and pushed into a database. From here, analytics and VISSMA backend is able to get data, to be shown in the VISSMA frontend.

Similar to the field deployment, a set of components has been developed as well for the laboratory to create an environment close to the real life for experimental work and analysis.

- RTDS: Models of the electric grid area for the realtime digital simulator has been developed and validated. See [D4.1].
- GRISE: To allow multiple, repeated validation tests, another tool, GRISE has been developed that allows to record and replay scenarios from the digital realtime simulator. This tool allows a fast way to generate data for statistical analysis but lacks closed loop grid behaviour. See [D5.2].
- VAMI: a component that were developed to analyse impact of data access strategies in the AMI network, as researched and developed in WP2. VAMI creates a virtual AMI that allows testing of approaches that are not possible in the real world, while being able to emulate conditions in the AMI network via communication models that has been created early in the project phase. See [D2.3], [D5.2].
- RT-DSSE: a system component that allows realtime distribution system state estimation as researched and developed in WP4. This provides estimates of the grid state similar to what is done in the real world (shown to the left), but in the lab setup, it is possible to compare directly with the true values, which is not possible in the real world. See [D4.2], [D4.3].
- AMA: A functionality for asset management that allows analysis of the grid for managing assets. See [D4.3].
- RemoteGRID Backend: VISSMA backend, database and a few interface components that allows to use the same VISSMA frontend in the lab as the one in the field deployment. Most here is similar to the backend in the field, but there are some differences due to different interfaces in the lab. See [D3.3].
- VHE: Virtual Head End system, which in fact is related to the VAMI component, but explicitly works as a virtual HE. Alarms in the lab are generated here as well as pushing the data collected via the virtual AMI to the database. See [D2.3], [D5.2].

The project was divided into three technical work packages focusing more on the research aspect of the process, which in the following, the highlights of the results will be presented.

1.4.2 Work package 2: Secure data collection and network configurations:

The core problem of this work package has been to model and assess new innovative ways to access information at the AMI level. Figure 8 shows and example of a concentrator that ensure access to three smart meters in order to use data for some purpose at some deadline, e.g. real-time DSSE functionality.

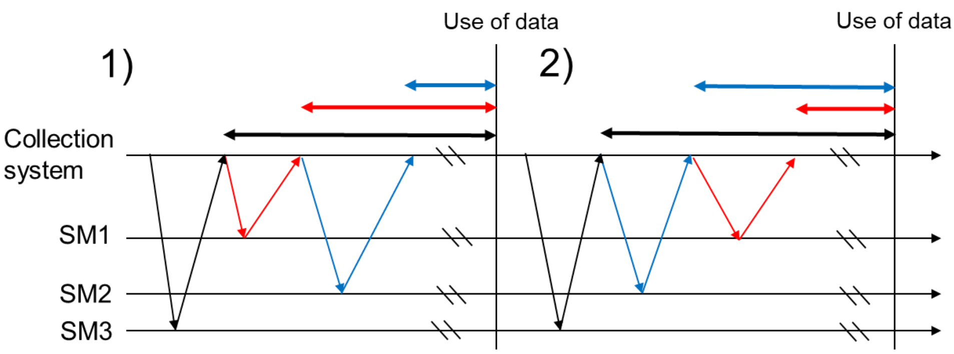

Figure 8: Timing and ordering of access to data and relation to age

To access three meters, there are several options, in the example here only two options are shown, where in both cases smart meter 3 as first accessed, then either number 1 or 2 is accessed. Thereby, the information age of the data from smart meter 3 is equal in both cases, but for meter 1 and 2, the order shows how the age of information leads to a significant change. In case 1) the meter data from meter 2 is younger than in case 2) and reverse for meter 1. The research question is therefor: which of these options are best and how can this be used algorithmic to prioritize data access? Use of information age does not give a proper answer to this question, but defining a metric, the so-called mismatch probability, we are able to see a difference that is meaningful. The mismatch probability is a stochastic metric, that is defined as *the probability of information being accessed in a certain way, is no longer matching the true value after some time,* [kemal16], [Kemal17]. An analysis of voltage levels, shown in Figure 9 this probability metric grows as a function of age. The interesting part here, is that this value is different from meter 1 and 2, which allows to prioritize the data, and in this case it is easy to see that meter 1 should be accessed before 2, as it statistically is more sensitive to being old than data from meter 2. We use this metric and analysis in an algorithm to determine the order of access in multiple meter

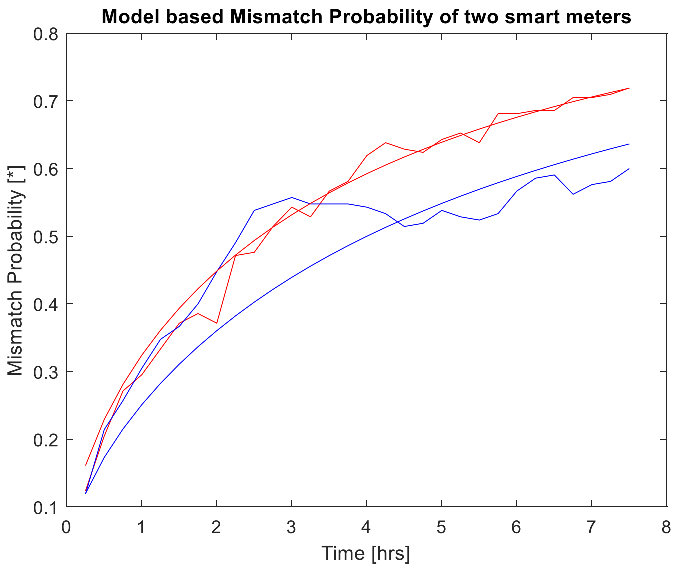

Figure 9: Mismatch probability as a function of information age

There are normally more than three smart meters under a concentrator, in fact a couple of hundreds is more realistic. However, that also leads to an order of 10^150-10^200 and more, possible combinations of access that in theory should be assessed. This is not realistic, so the project developed a heuristic algorithm to determine a good strategy (although not strictly the best), [kemal18a], [kemal18b].

Figure 10: ODAS algorithm performance under different cases, [kemal18a].

Testing this algorithm with 10 smart meters, it was possible to compare the true best and worst access approach with 1) the algorithms proposed one, and 2) 10.000 randomly selected approaches. The result, measured by mismatch probability, is shown in Figure 10, done for various cases. The important message from this result is that the algorithm (ODAS, marked with circles) generally is close to the best case (the lowest arrow) for each case, compared to the random guess (marked with a cross). Remark here that for a number of smart meters higher than 11-12 the amount of possible strategies becomes so high, that upper and lower boundaries cannot be calculated, [kemal18a].

During the project, the affiliated PhD student had a secondment at Chalmers University, where he worked on how to identify and mitigate cyber-attacks on smart meter infrastructures. The basis was a smart grid voltage control loop that creates set points for photovoltaic based on measurements from smart meters. Using machine learning an identification algorithm was able to detect if a DOS attack, replay attack or data integrity attack was taking place. The mitigation techniques was to shift from using real meter data to state estimate data which links the detection of attacks to the use of grid state estimation done in WP4. The results have led to a couple of papers published in the scientific environment, see [D2.2] and [Kemal19].

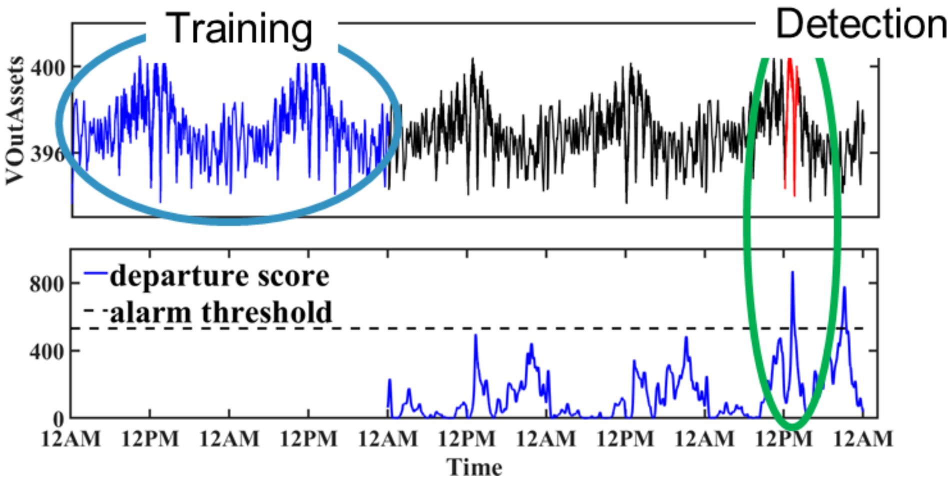

Figure 11: Example of smart meter measurements time series used to detect a DoS attack on the AMI infrastructure, [Kemal19]

In addition, the outcome of the work package also lead to a java based tool VAMI (Virtual AMI) that allows testing in the laboratory of access policies over different AMI network conditions. This tool has extensively been used in the lab for various assessment purposes.

1.4.3 Work package 3: Database, data processing and visualization

This work package has several key outcomes. The first is related to the database used. Initially, when the project started, all relevant data related to grid topology, GIS information and smart meter data were in different subsystem using various indexing methods. The initial outcome of the project in this regards were to device and setup a database structure that allows a simpler approach to link data together jointly, but which also respects privacy. A key challenge here has been to ensure that data is at the same time is kept apart to disallow a random person to link any measurement directly from the database to a household or even an owner. This has been done via special keys that in reality only the VISSMA backend is allowed to use. Persons who has access to the database may be able to link data together, but is not a trivial task.

The second key outcome of the work package, is the visualization tool, VISSMA (Visualisation System of Smart Meter dAta), which contains of a front- and backend subsystem. The front end is a JavaScript based web client that the user interacts with via a browser, while the backend system is a .NET based server that handles the interaction with the database and front-end client. The design of the front end has involved a process of user interaction studies engaging students from Aalborg University who specializes in user interactive design studies, wherein work flow analysis has been carried out. This process has in itself gained much attention and shown to be useful for Thy-Mors Energy.

A screen shot of the VISSMA front end system is shown in Figure 12. On the main part, the operator can get an overview of the electrical grid in terms of cables, cable boxes, customers that are connected, substations etc. All elements are clickable and more information can be shown which are found by lookup into the RemoteGRID backend database.

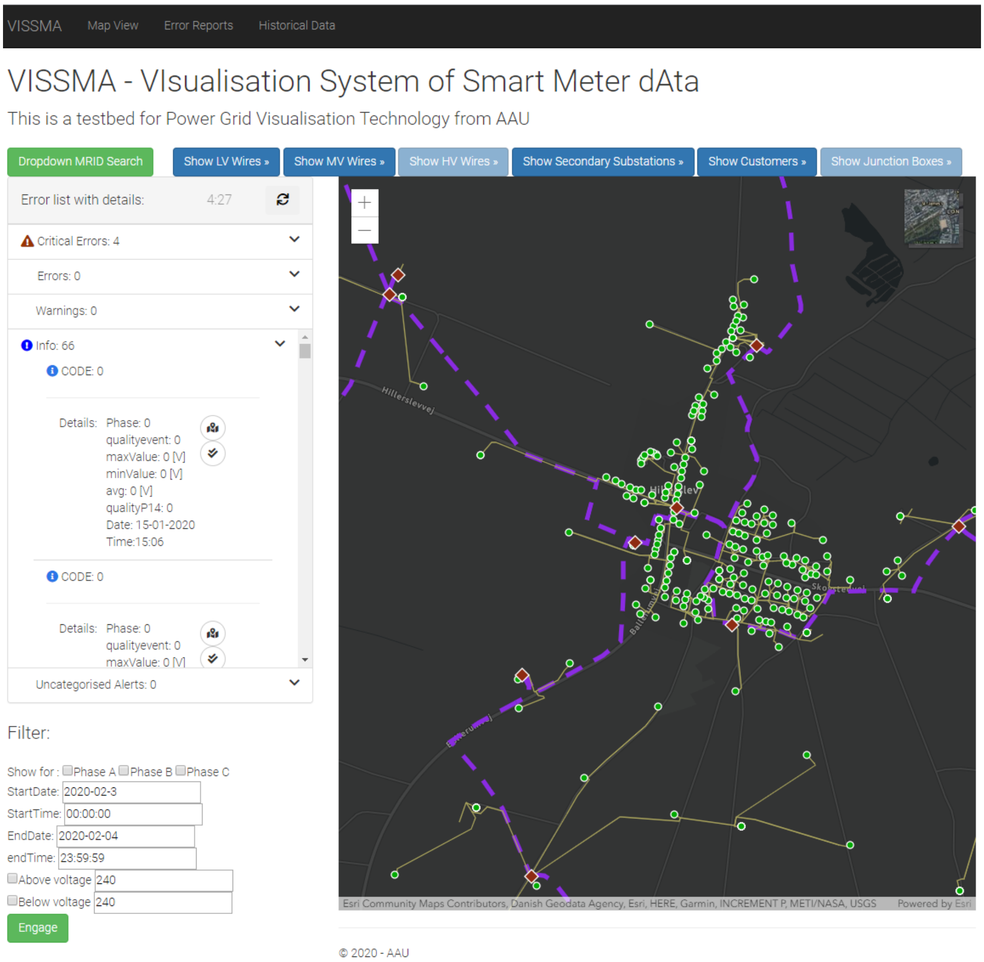

Figure 12: Screenshot of VISSMA viewing a smaller town on Thy

The database allows to perform certain actions, and to the lower left side of Figure 12, there is a filter, which allows the operator to show only those meters which inside a specific time period (as specified), has voltages higher or lower than some inputted value. This can be done for one, two or all three phases of the grid lines. Further filter types have been discussed, but not implemented.

Alarms and events that are logged and transmitted over the AMI and via HES, are shown in the left side, and made clickable so that operator jumps to the correct location, opens a screen and zooms to the relevant time around the event or alarm. The screen that opens (which is the same as if one just click on a button) is shown in Figure 13. In this screen, the time series of voltages, currents, power (active and reactive) are shown for the selected item. Maximum and minimum values are also shown, in addition to specific information and statistical information about the node itself.
Although not integrated, the purpose is that via the DSSE and asset management functionality, this information are also shown for cables, cable boxes from which normally there are no measurements available. If that last step is done, the tool would truly provide value for the DSO.

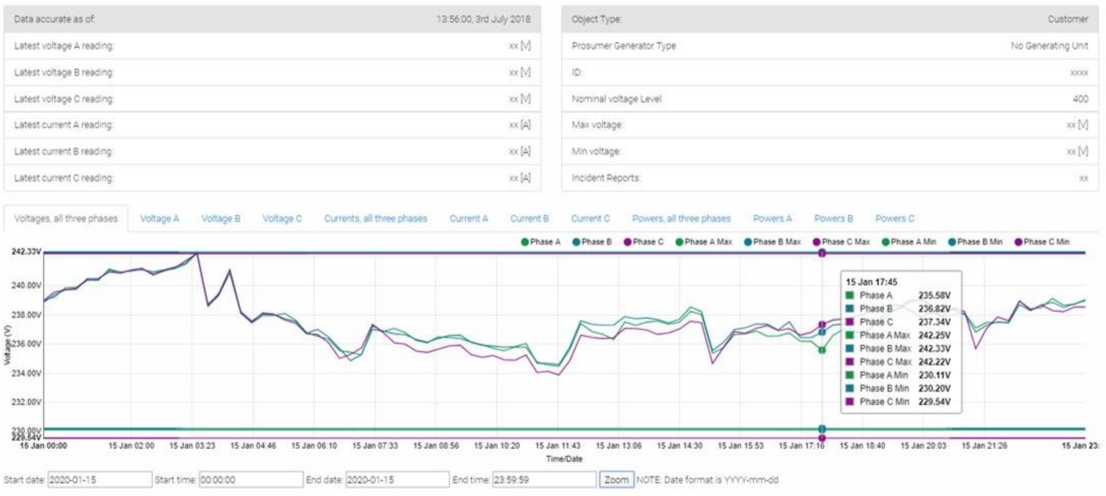

Figure 13: Example of voltage view over time for one meter in the test area

A part of the work in this work package has also focused on the structure and organization of the database, which is key to the performance of such system. The true structure is too large to cover for this deliverable, but see [D3.2] for details. Instead a brief overview of the required data in the database is shown in Figure 14.

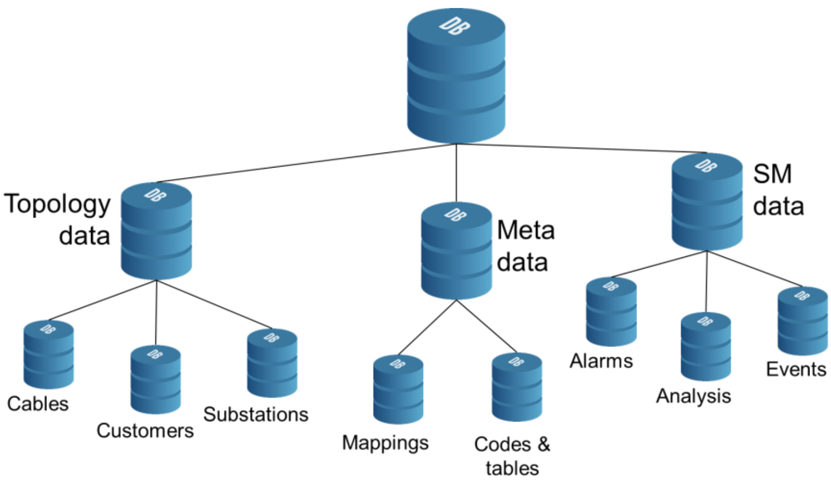

Figure 14: Overview of database and the internal structure of main tables

To support the various functionalities that does require computational resources and event driven processing (it is not realistic to continuously process data from all meters at all time), a supporting processing and flow oriented database is required. The process and related tools were assessed in [D3.2] and a rough sketch of the process is shown in Figure 15.

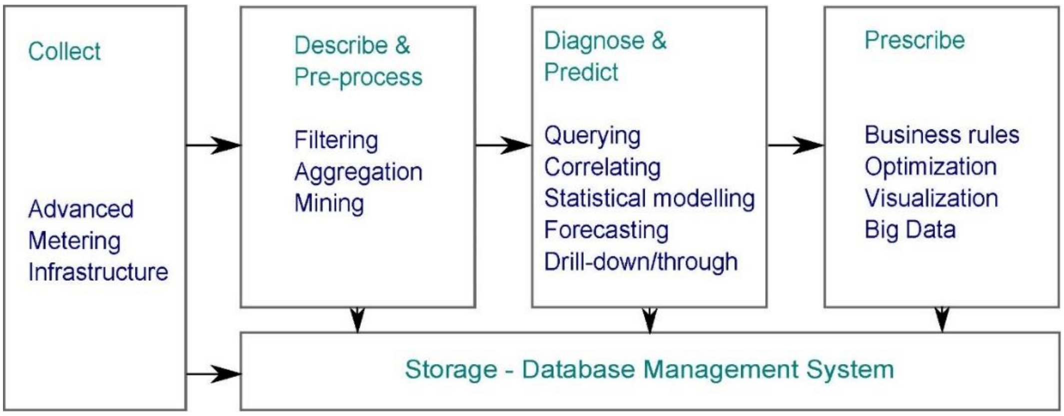

Figure 15: Data conversion processes, [D3.2]

The critical point here is that data analytics is broken down to smaller, focused tasks starting from description and pre-processing steps, followed by diagnosis and prediction and eventually prescribing step.

1.4.4 Work package 4: Real time state estimation and asset management

In this work, distribution system state estimation (DSSE) algorithm is developed for estimating the states of LV grids from smart meter measurements. The intended applications of DSSE in RemoteGRID project are near real-time monitoring and asset management. The schematic diagram of the distribution grid along with ICT infrastructure is shown in Figure 16.

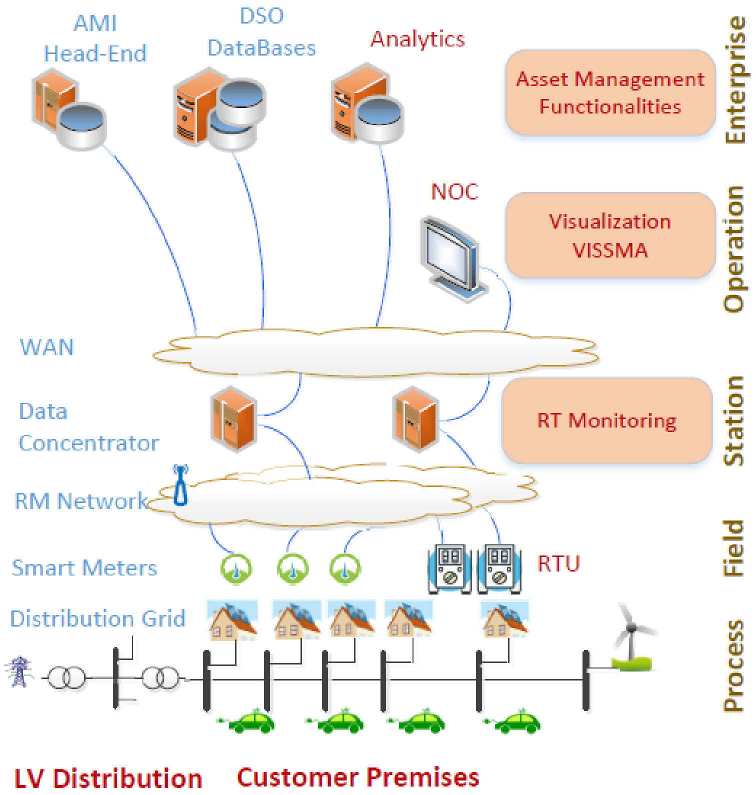

Figure 16. Schematic diagram of LV grid and proposed locations for implementation of DSSE algorithm.

The main objectives are to develop a DSSE algorithm for the following applications:

- **Near real-time monitoring of LV grids** - Estimation of node voltage phasors close to real time with minimum real measurements and pseudo-measurements at nodes where real measurements cannot be obtained. The estimated voltage phasors provide full observability of the LV grid to the DSO and help them to take proper control actions to maintain the grid voltages within allowable limits.

- **Asset management of LV grids** - Estimation of grid energy losses, loading of grid assets such as cables and transformer, estimate the ageing of cables, investigations of power theft, and identification of mismatch in LV grid parameters.

The major outcomes of this work are:

- DSSE algorithm based on nonlinear weighted least squares method which is numerically validated by simulations carried out on a model of Feeder 5, Area 2 of TME 10/0.4 kV LV grid.
- Sensitivity analysis of the DSSE with respect to magnitude of errors in measurements, number of measurements etc.
- Simulation studies about the application of the developed DSSE algorithm for the above mentioned two use cases.

	Near real-time grid monitoring	**Grid asset management**
Measurements	Asynchronous or synchronous	Synchronous
Number of measurements	$M \leq S$ where, M is the number of smart meter and pseudo measurements and S is the number of grid states	$M > S$
Observability analysis	Required	Not applicable
Sensitivity analysis	Required	Desirable
Type	Single-phase equivalent DSSE assuming grid to be balanced	Three-phase DSSE
Grid model	Linear model (approximate) or nonlinear model	Nonlinear model (Exact)
Method	Nonlinear weighted least squares or Kalman filter	Nonlinear weighted least squares
State variables	Voltage phasors	Voltage phasors or branch currents in rectangular coordinates
Accuracy requirement	Moderate	High

Table 2: Comparison of requirements of DSSE algorithm for its proposed applications, [D4.3]

A generic block diagram of the DSSE algorithm is shown in Figure 17. In this work, nonlinear weighted least squares method is used in the DSSE formulation.

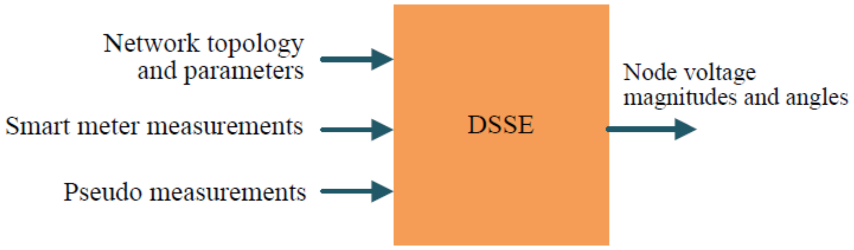

Figure 17. Block diagram of DSSE, [D4.3].

The ePHASORsim module of OPAL-RT is used to model the LV grid. Load profiles of all the customers in all three phases are given as inputs. The true values of grid states are obtained from the OPAL-RT offline simulations. These are used for comparison with the outputs of DSSE algorithm to compute its accuracy.
Regarding the application of DSSE for near real-time monitoring of LV, the following results were obtained. Sensitivity analysis of DSSE is done with respect to measurement errors, type and location of additional measurements, pseudo measurements, and grid parameters reveals the following facts.

- Sensitiveness of DSSE to uncertainties in the order from high to low level can be written as (1) location and type of measurements, (2) pseudo measurements, (3) grid parameters, and (4) measurement errors in smart meters.
- Voltage measurements from far end nodes are highly useful to minimize the sensitivity of DSSE to uncertainty.

An example of DSSE results when including additional measurement points are shown in Figure 18.

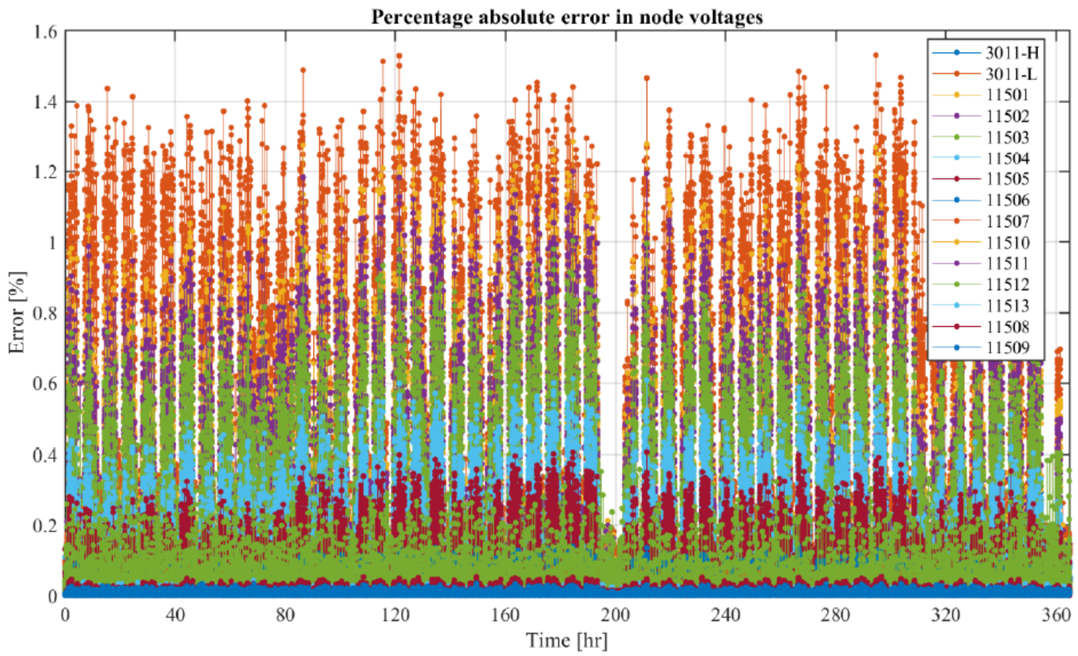

Figure 18. Example of percentage absolute error in node voltages estimation based on Type 2 profile pseudo measurements, [D4.3].

Regarding the application of DSSE for asset management, the simulation studies shows the following.

- Three-phase DSSE is better than single-phase DSSE to estimate the grid power losses and loading of grid assets such as cables.
- Load unbalances are captured only in the calculations of three-phase DSSE making it the right choice for asset management.

Simulation results showing the estimation of specific cable loading in the test area is shown in Figure 19.

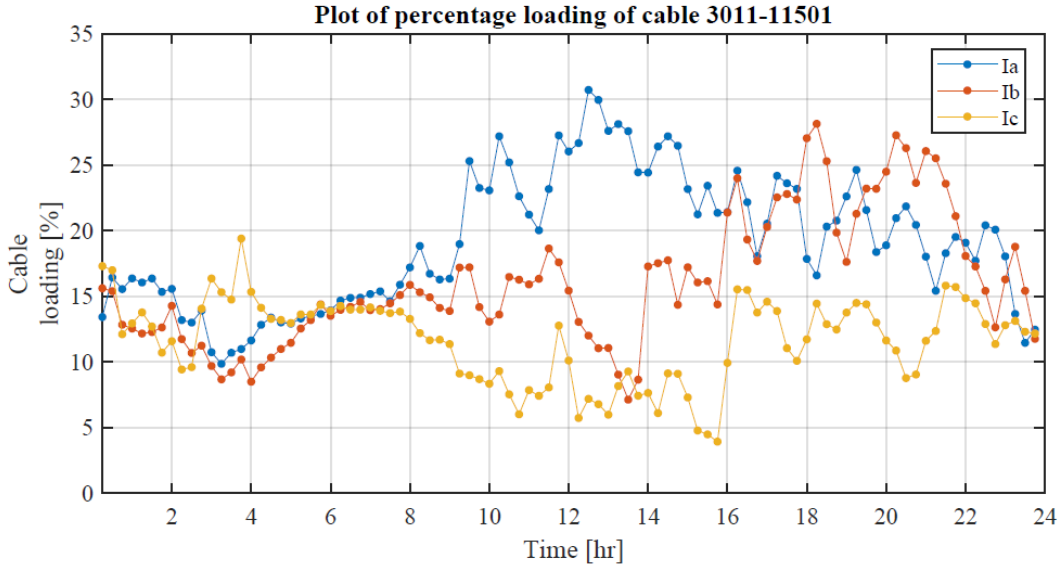

Figure 19: Example of cable loading estimation as provided by asset management functionality, [D4.3].

An example of estimating grid losses using the two proposed algorithms i.e. single- and three-phase DSSE is shown in Figure 20.

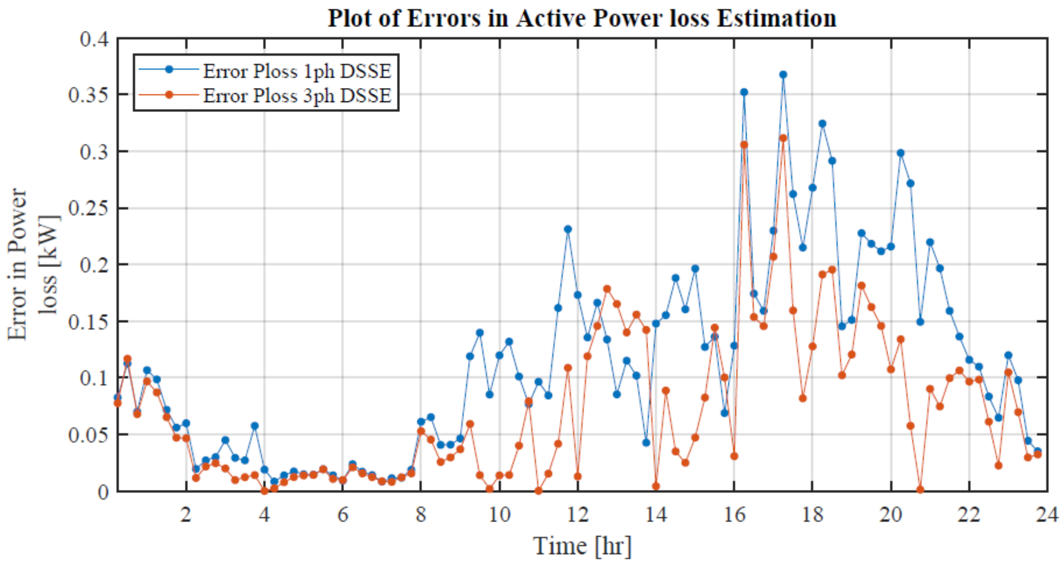

Figure 20: Plot of errors in estimation of active power losses in Feeder 5, [D4.3].

From the simulation studies conducted on model of the test LV grid of TME, the following overall observations are made:

- DSSE is sensitive to noise in the measured smart meter data and its accuracy may be reduced, if there is a significant amount of noise in the measured signal. The effect of noise on DSSE may be minimized by incorporating more measurements e.g., RTUs, especially node voltages into the DSSE algorithm.
- Accuracy of DSSE can be enhanced by adding node voltage measurements as inputs. It is found that measuring voltages from far end nodes is beneficial, as the voltage sensitivity is high at end nodes.
- For near real-time monitoring of LV grids, it is impractical to get smart meter measurements from all nodes. Hence, the historical data from some of the nodes can be used as pseudo measurements. By doing so, the accuracy of DSSE will be impaired. From simulation studies, it became evident that DSSE is very sensitive to errors in pseudo measurements. A solution to improve the accuracy is to include voltage measurements from far end nodes.

The following recommendations are made based on the knowledge obtained from the application of DSSE to real-time monitoring and asset management.

- It is important to know the expected amount of noise in the smart measurements and to calculate its impact on the performance of DSSE. Suitable weighting factors may be used in the nonlinear least squared algorithm. These weighting factors should be selected based on how reliable the measurements are in practice.
- Sensitivity matrix can be computed for the LV grid under study using grid parameters for normal loading conditions. From the sensitivity matrix of the LV grid, the most sensitive nodes are to be identified and their voltages may be measured through RTUs, for inclusion in the DSSE. If the grid topology changes, or there is a major change in power consumption profile, or there is an addition of new renewable sources or electric vehicles, then the sensitivity matrix has to be recomputed again.
- To minimize the number of smart meter measurements, many of the residential loads which have similar load profile may be considered as pseudo measurements and their consumption pattern may be predicted from their historical data.

Regarding practical implementation of DSSE for near real-time monitoring the project recommends to implement the algorithm at data concentrator level as a collaboration between DSO (having the knowledge of the grid topology, customers and other related parameters) and AMI provider (having the HW and access to SM measurements). Nevertheless, DSSE can be gradually implemented starting with those substations facing challenges such as voltage unbalance (due to high penetration of RES) or transformer overloading (due to addition of extra loads such as EV) etc. Then, over time, a full deployment can be achieved. Furthermore, the pseudo-measurements are to be computed at enterprise level based on certain rules (e.g. season, month, etc.) and provided to substation level.
The main challenge for asset management applications is to store SM data effectively, such that DSOs can see historical profiles (e.g. for the last 2-3 months or even more). Furthermore, implementation of asset management will not only require data from SMs but will also depend on information, such as, grid topology and the related parameters, customers, GIS, alarms, etc. Thus, a new type of database will be required, which could merge information from several existing databases. A possible solution to this can be the

development of dedicated adapters responsible for accessing and collect required information from the existing databases and making it available for the DSO.

1.4.5 Work package 5: System development, integration and test

This work package has had the objective to ensure that technical work in work package 2, 3 and 4 are integrated and evaluated. Two approaches have been considered: 1) test bed setup that allows realistic testing of asset management algorithm in a hardware-in-the-loop setup hosted at Aalborg University, and 2) feasibility study in an operative environment hosted at Thy-Mors Energi, where in particular the visualization concepts will be demonstrated and tested for daily operations and planning/management of the electrical grid.

An overview of the envisioned deployment view of RemoteGRID functionalities is given in Figure 21. It captures both site-test and RT-HIL laboratory setup including main components and sub-systems. The site-test is comprised mainly of the existing AMI system, the Head-End system, visualization system and databases in the cloud provided by Kamstrup. Data is via VPN tunnels exported by Kamstrup's HES to a blob on an Azure cloud hosted by Kamstrup, from which data and signals are forwarded to RemoteGRID backend database, from where the visualization screen located at TME premises access data. This design was not originally planned, but a result of ensuring that security requirements were met, and that GDPR compliancy could be met as well. The visualisation system (VISSMA) is constructed by a front and backend part, for which the backend is located in the TME Azure cloud and is the main location for new functionalities, and the frontend at a machine at TME, which allows simple interaction with the human interface and the backend. To support the data flow between TME and the TME Azure cloud, another VPN tunnel is established. In addition to this, there may also be a need to connect with a VPN tunnel from the laboratory to the database on the cloud, allowing to push simulated data to the RemoteGRID database that can later be shown on the VISSMA frontend. This is most useful for e.g. training sessions or 'what if' scenarios, which can be used at TME premises.

The Laboratory setup is not linked directly with the field test system and it is not using consumption or production data from DataBase, and data from lab is stored in a separate database, which is accessed from a shadow version of VISSMA, to ensure absolute separation of the two data paths.

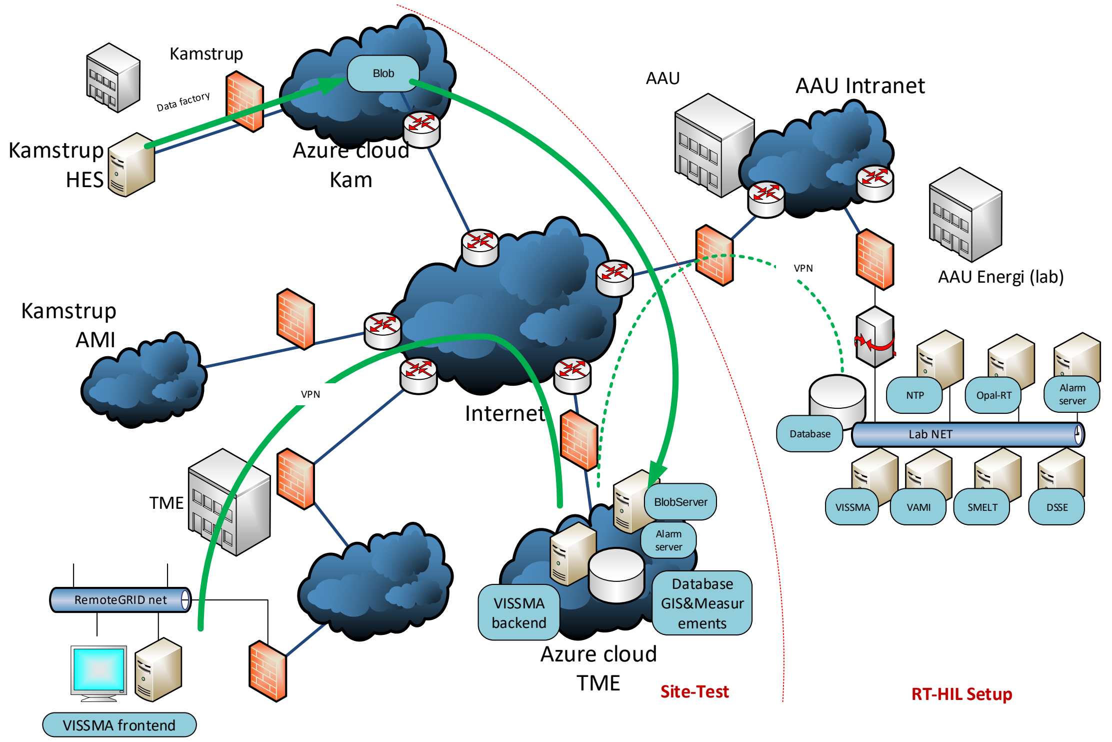

Figure 21: Detailed deployment overview for RemoteGRID project

The main components related to Site-Test are as:
HES: Head end system; the main interface to the complete AMI system provided by Kamstrup.
AMI: Advanced Metering Infrastructure; the complete network of smart meters, data concentrators and radio mesh network used to carry data to the HES from the smart meters.
TME Azure Cloud: Cloud solution that allows hosting of the humongous amount of data that will be collected in the project. This will act as a data lake to feed data into VISSMA.
Kam Azure Cloud: cloud used for storage of Blobs containing the historical data from smart meters and from event loggers.
VISSMA: Contains a front end and backend solution for the visualization platform of the data.
DataBase: Holds data measured by smart meters in Site-Test, as well as the required GIS data.
BlobServer: a service component that checks and fetches information from the Kamstrup HES via the Kam Azure cloud, and injects data into the database. This approach fulfils the strong required security and tunnels that are needed to ensure data path is secure at all time.
AlarmServer: interfaces and accepts alarms from the Kamstrup HES.
A set of tools and components are developed for the laboratory implementation in order to perform research, training and further assessment of the work being carried out, see [D5.2].

Interfaces between components are split into two main parts, namely those in the RT-HIL setup and those in the Site-Test. Most interfaces are same in both field test and lab setup, to ensure simplest integration and tests as possible. Updates in one place are then easily ported to the other site, meaning that maintainability is reasonable easy.

TME Site Test

The distribution grid used in the field trials is located north of Thisted, North Jutland in a smaller village, and comprises of 3 secondary substations as shown in Figure 22. These three substations are part of a 10 kV MV feeder supplying power for the entire area. The locations of these secondary substations on the MV network is shown in Figure 23.

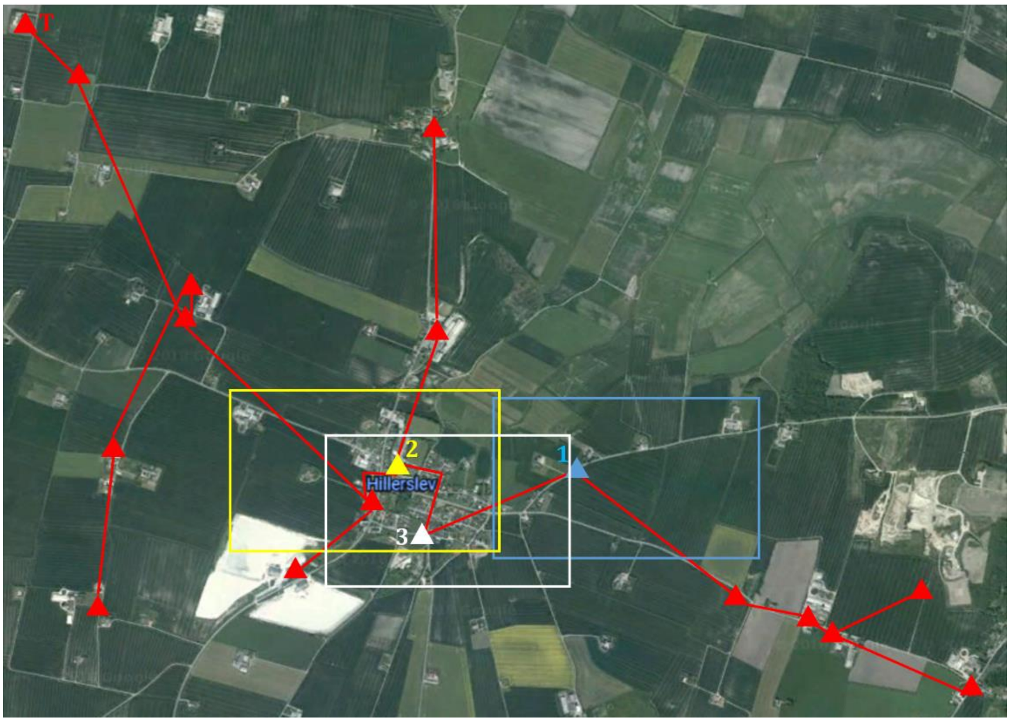

Figure 22. Google map of site test area, with area 2 as the selected one.

In [D5.1] the area for analysis and testing were chosen as number two of the three shown in Figure 22. The secondary substation of Area 2 feeds a total of 91 customers as depicted in Figure 24. Typical load curves differ from customers since there is mixture of households, commerce and small industry in this area. The penetration of renewable energy resources is of ~5% of the total number of customers with five PV installations of 5.5, 6 and 10 kW rated power respectively. There are no wind turbines connected to this substation.

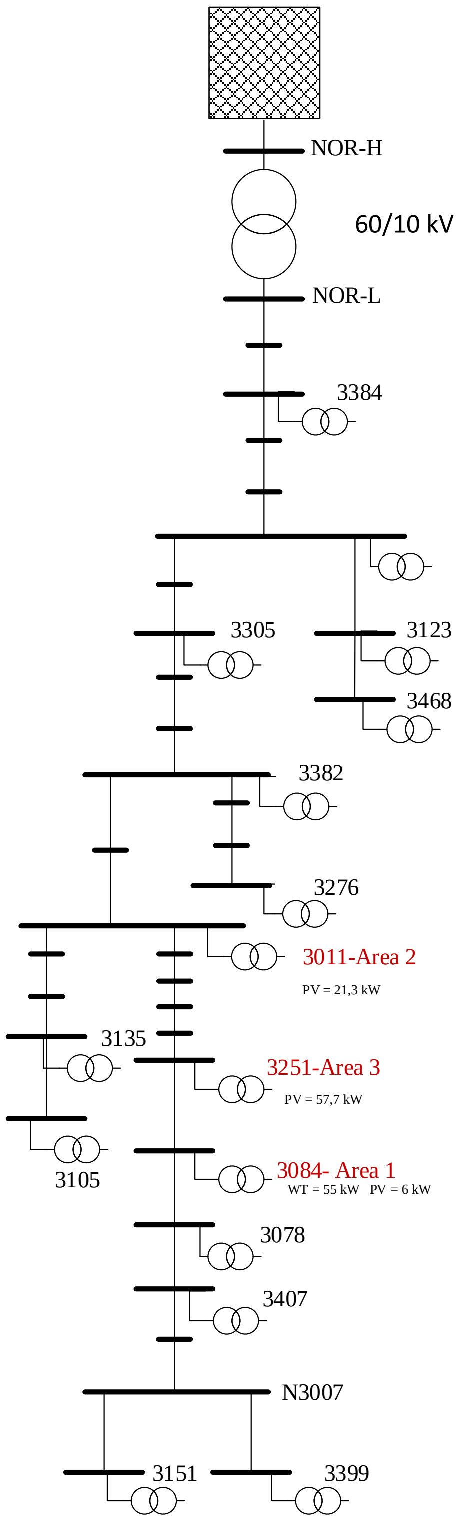

Figure 23. Single Line Diagram for the MV grid.

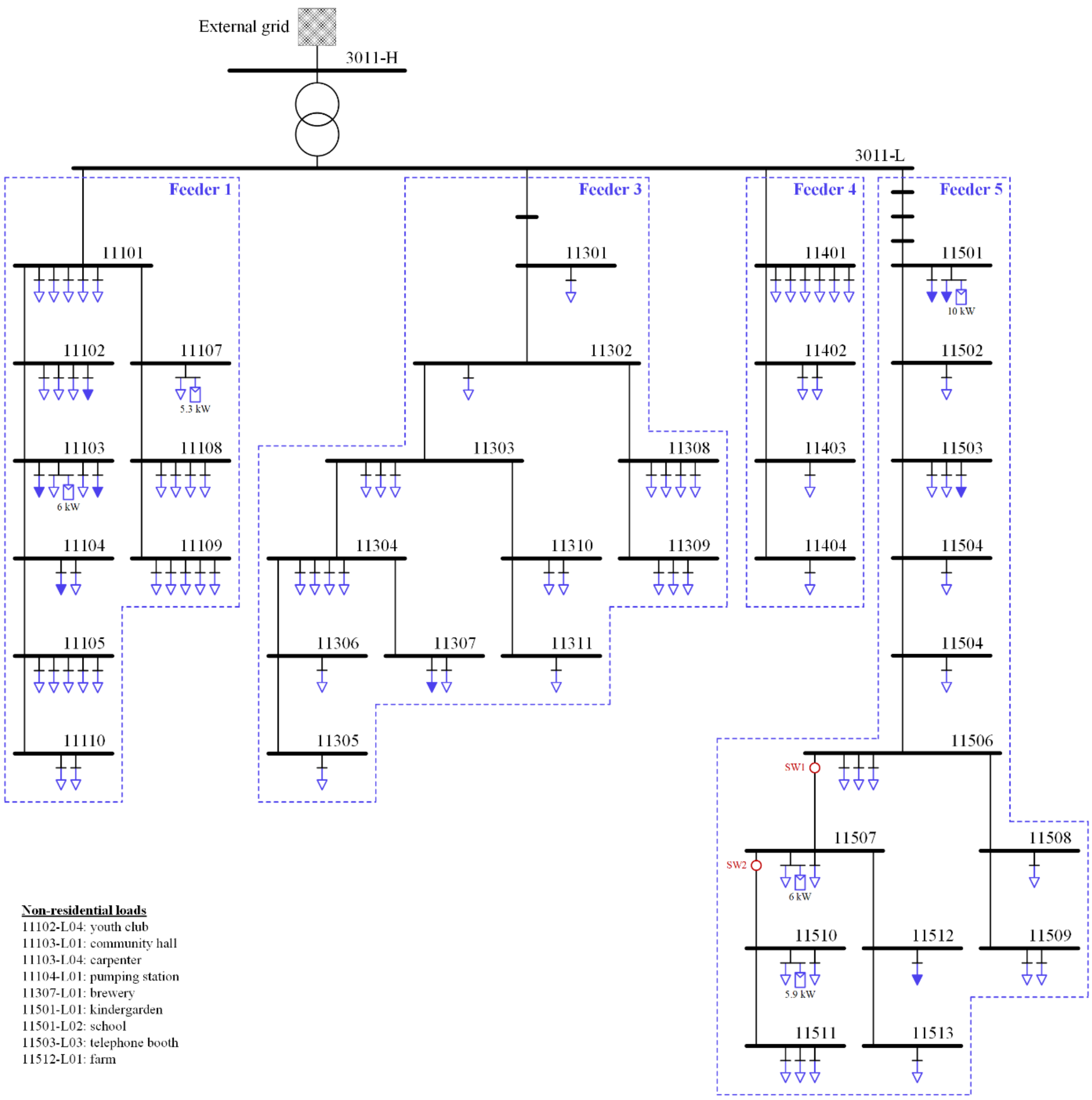

Figure 24. Single Line Diagram of Area 2.

In all SLDs the customers are represented by a load sign (power system convention) connected to a small blue terminal which represent the customer electrical switchboard. Then a small cable (red or blue)) is making the connection to the junction box on the street. The length of this cable is typically unknown. All PV installations in the site test area are connected to the electrical switchboard of a given customer. The site test area has high penetration of smart meter deployment, both at the customer premises and at 10kV level. Furthermore, fiber-optic cables are covering the area.

Laboratory RT-HIL

RT-HIL setup used in project is a cyber-physical system comprising of different domains i.e. hierarchical control, Information and Communication Technologies including their traffic, electrical power grid that operates in Real–Time. An overview of the setup for RemoteGRID and the related lab components is shown in Figure 25.

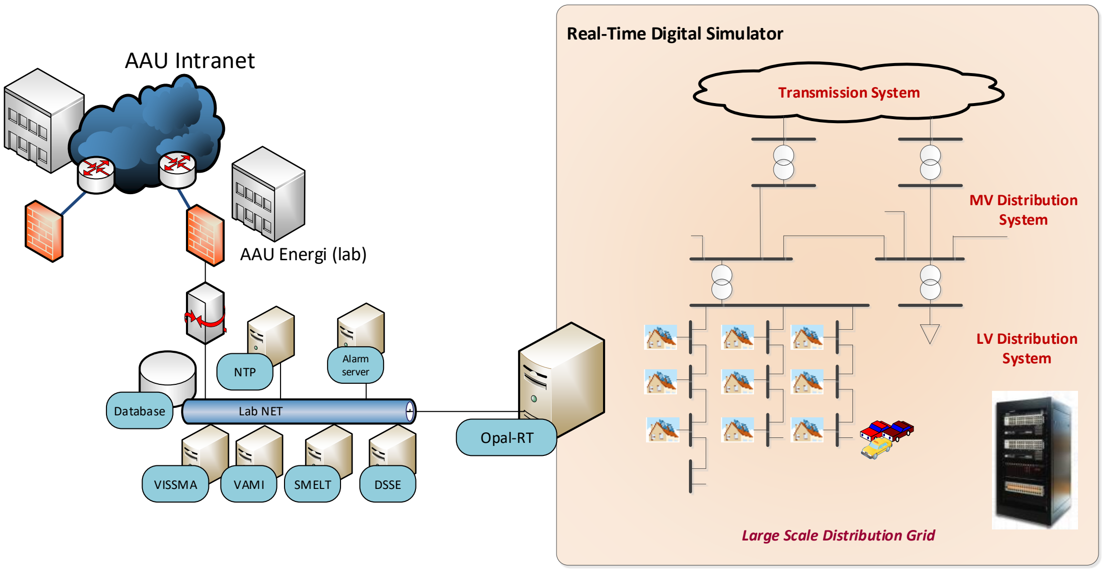

Figure 25. Overview of RT HIL setup used in RemoteGRID Project.

VAMI (Virtual Advanced Metering Infrastructure): A software component that emulates data packets path through an AMI. Structure follows the Kamstrup system, with smart meters, data concentrators and Head End systems, and adds various meta data to the output data that are useful for performance assessment of the system and AMI configuration.

GRISE (GRId Simulation Emulator): A simple Java based tool which reads any previously generated grid data (or measurements) and puts them into proper UDP packet format to emulate a data source that feeds VAMI and later the visualization part.

SMELT (Smart Meter EmuLaTor): A small Matlab based GUI that allows to directly manipulate smart meter values and output those in the proper UDP packet format to be fed into the visualization part. It has no connection to an actual grid, and therefor really emulates only a single, isolated smart meter. It may be used for e.g. training or testing purposes, and works in Real-Time.

VISSMA (VIsualisation System of Smart Meter dAta): A set of components that allows visualization of data onto a GIS based screen. It consists of a client and a backend service, which allows efficient display and proper scaling of data being visualized as well as event notifications etc. Notice that this component is basically the same for both Site-Test and RT HIL setup. VISSMA is split internally into a front end and a backend. Front end is light weight and enables browser access, and backend contains the processing heavy parts.

NTP (Network Time Protocol server): Network based time synchronization protocol. It is important that all involved machines are fully synchronized in time, and using this system, time stamps are guaranteed synchronized to the level of some 10 ms. to each other.

Opal-RT: a powerful Real-Time Digital Simulator built around a dedicated software that enables large scale modelling of electrical grid. All the three areas from the Site-Test including the MV feeder are modelled in Opal-RT.

AlarmServer: interfaces and accepts alarms generated by the virtual smart meters and send by the Virtual AMI (VAMI). Interfaces are made based on the Kamstrup HTTP/XML specifications such that the same alarm server in principle could be used in the field test setup as well.

Project Approach

The project has elaborated a set of User Stories and Evaluation Criteria for them as part of demonstration strategies. The set of user stories has previously been defined in [D1.2], as:

<UserStory-1: Improved low-voltage grid observability>

<Userstory-2: Asset management>

A set of evaluation criteria (EC) is then linked to the user stories. The EC are using the work flow of a DSO and it is based on the daily operational flow at the DSO.

Evaluation criteria for UserStory-1:

US1-EC1	A reduction in process steps of ≥75%/SM
US1-EC2	Provide an updated picture of operational parameters in the low voltage grid within a time window of 6 hours including deviations.
US1-EC3	Reduce the no. of software applications needed to operate in order to display grid state to one

Table 3: Overview of evaluation criteria for improved LV grid observability

Evaluation Criteria for UserStory-2:

US2-EC1	The solution shall reduce the existing asset management planning process by 25%
US2-EC2	The solution shall be perceived as a useful tool by at least 75% of operators involved in asset management

Table 4: Overview of evaluation criteria for asset management

A complete workflow comprising of seven stages was also established [D5.2] that was mapped on user stories and test cases. A summary of this mapping is shown in Table 5.

	Site Test	**RT-HIL Setup**	**Remarks**
Stage 1	**x**	**x**	RT-HIL Setup is involving 2 phases: Phase 1 involves GRISE and SMELT in an open-loop approach Phase 2 involves complete Site Test representation in Opal-RT with all sub-systems in closed-loop
Stage 2	**x**	**x**	
Stage 3	(x)	**x**	
Stage 4	+	**x**	
Stage 5	+	**x**	
Stage 6	not possible	(**x**)	
Stage 7	(x)	(**x**)	

Table 5 Overview of Project Stages and their realization. Legend: An x indicates targeted and achieved, a % indicates targeted but not achieved, a + indicates achievements beyond the original target and () indicates partially achieved

The table indicates that most parts have been achieved in the lab setup and in the field test. The stage 3 in the field only covers the events logged by the smart meters, which arrives with the same data as voltages and power levels. Alarms has not been integrated as for technical reasons this has not been possible at this time. Stage 4 and 5 were implemented and tested in the laboratory setup, while a complete integration was achieved on Site Test. Stage 6 and 7 were developed and assessed in WP4 though off-line simulation studies using the same model for electrical grid as in the Real-Time co-simulations.

Stage 6 requires, as recommended in [D4.3], implementation of near Real-Time DSSE at Data Concentrator level with additional measurements points in selected junction boxes for accurate estimation of the grid states. Pseudo-Measurements must also be generated according to historical profiles before running the near real-time state estimation algorithm. Modifications on the actual data collection mechanisms including data storage and additional calling functions must be implemented on Data Concentrator, AMI Head-End and Data Base. Thus, Stage 6 cannot be demonstrated in Site Test without interfering with the actual production system i.e. data collection for billing. The same challenges are applicable to laboratory demonstrations. Stage 6 was instead achieved in laboratory using a simplified setup for ADCM, generation of Pseudo-Measurements and considering additional voltage measurements in selected junction boxes. A complete integration in the envisaged RemoteGRID deployment architecture was considered out-side the scope as the functionality was demonstrated in a simplified setup and guidelines for practical implementation were derived.

It has been found that Stage 7 too imposes integration challenges on Site Test. As documented in [D4.3] asset management functionalities requires a three-phase representation of the electrical grid and voltage, active and reactive power measurements available for every phase as well as generation of Pseudo-Measurements and additional voltage measurements. The required granularity of the Smart Meter measurements was available from the Site Test in Q3 2019. Moreover, in order to implement this functionality on Site Test a translation of the original code, i.e. Matlab, developed in WP4 to a programming language (e.g. Java, Python, etc.) compatible with the deployed hardware in TME is required. Moreover, the results of this algorithm shall be added into the data base then linked to VISSMA for on-demand execution and visualization on screen. A final software implementation and integration for this application was not initially in scope of RemoteGRID. Instead, the functionality was tested and demonstrated off-line using the required Smart Meter data as provided from Site Test for a one representative day only. Longer time intervals e.g. 1 month, 6 months or 1 year were not possible due to missing historical data. A simplified setup that is not accounting for actual links and interactions between Back-End and VISSMA was also used. Integration of Asset management functionality on Site Test will be in scope for a follow up demonstration project.

The defined use cases where implemented and tested in both Site Test and laboratory RT-HIL framework.

Example US1-EC2 (Updated view of operational parameters in LV grid)

This UseStory was related to visualization of low voltage grid. The VISSMA – VIsualiation System and Smart-Meter dAta provides an overview of the low-voltage Grid in the Test-Area 2. The VISSMA tool is presenting data from individual databases comprising topology data, Smart-Meter data from the AMI database and advanced alert features provided by push functionality in the Smart-Meter management software. Figure 26 exemplifies the operational image of the LV-status.

Figure 26: Example of voltage levels on Jan. 15, 2020 at one of the nodes in the test area.

Same UseCase was also demonstrated in laboratory RT-HIL framework.

One of the main advantage of using the laboratory framework is the possibility in changes the update rates for signal exchange between various systems and components. Thus, any event occurring in the distribution grid can be shown in VISSMA by configuring the desired value for the update rates in VAMI (see Figure 27). Thus, the visualization of grid states and events can be made every minute or even faster according to training needs. A very fast streaming functionality i.e. second based, is also considered for future demonstrations and applications as a tool for exploring "what if" scenarios.

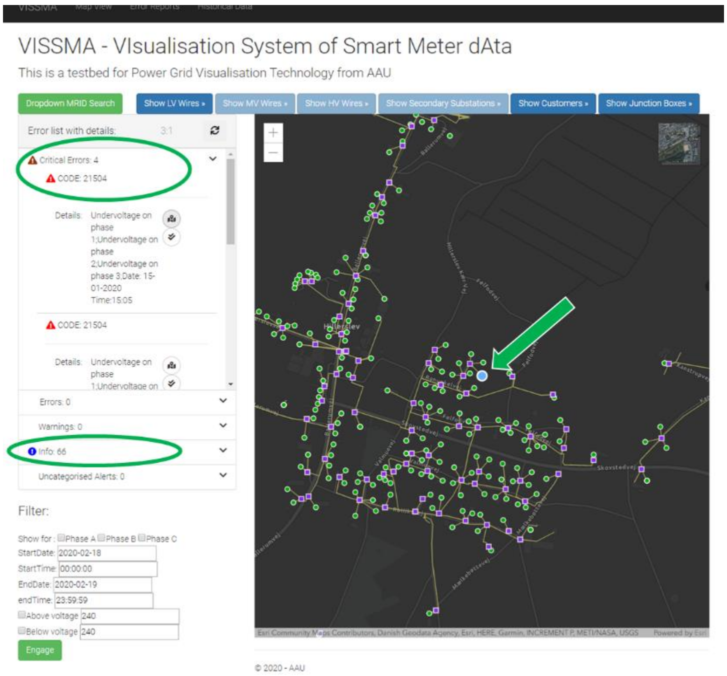

Figure 27: Screenshot of VISSMA front end, with focus on alarms and info fields. Notice the blue enlarged measurement point, which indicates the location of the selected alarm to the left

In Figure 27, a screen shot is taken from the GUI, which points to the location of events and alarms registered in the system according to actual settings in AMI.
When opening the list of errors (as shown in Figure 28), there is a button to jump to the location of the event. When clicking on this, the specific location changes to a larger icon on the screen (the blue large dot, that the big arrow points at), and a screen pops up which contains the data around the time that the event or alarm happened at. This relieves the operator of spending time and effort into finding both the location and time that is of interest to the particular alarm or event.

Figure 28: Overview of an example run with the OPAL-RT, where loads are first increased leading to under voltages, and after a normalization the production of PV energy is increased leading to an over voltage situation. Node shown here is a neighbouring node.

In the lab setup, this happens for alarms in near real-time as alarms are passed specially in the VAMI to the HES, which then feeds directly alarms into the database. The error list is the updated every so often (configurable) with a countdown timer to show when next update is due, and a refresh button to manually update the list. Events are accessed at the same time as with other smart meter data, but are located in a special table, and provides detailed information about special events such as over voltage, and what exact time that happened. More notifications for errors and warnings can be added and tested according to future developments in the Smart Meter core functionalities. Moreover, new errors and warnings can be easily implemented in VAMI then tested in laboratory framework. All targeted UseCases for site test are documented in [D5.2].

VISSMA will continue to be used in TME's Network Operation Center beyond RemoteGRID. The feedbacks as well as the user experience will be monitored and collected for a future release.

1.4.6 Work package 6: Dissemination and exploitation

In work package 6, the work has been focused on dissemination of the project results. This has mainly been through scientific conferences and journals in conjunction with the work of the Ph.D. students. In total the following conference papers has been achieved in the project time period

- (Position Paper) Characterizing the Behavior of Small Producers in Smart Grids. A Data Sanity Analysis, Computer Science

- Enabling Smart Grid Features by Enhanced Utilization of Actual Advanced Metering Infrastructure, CIRED
- Exploring the Potential of Modern Advanced Metering Infrastructure in Low-Voltage Grid Monitoring Systems, IEEE International Conference on Big Data (Big Data).
- Model-Free Detection of Cyberattacks on Voltage Control in Distribution Grids, EDCC
- Data Analytics for Low Voltage Electrical Grids, IEEE IoT, Big Data and Security
- Optimized Scheduling of Smart Meter Data Access: A Parametric Study, SmartGrid-Comm
- Optimized Scheduling of Smart Meter Data Access for Real-time Voltage Quality Monitoring, ICC workshop
- Information Quality Aware Data Collection for Adaptive Monitoring of Distribution Grids, SGIoT
- Observability of Low Voltage grids: actual DSOs Challenges and Research Questions, Int. universities power engineering conference
- On-line Configuration of Network Emulator for Intelligent Energy System Testbed Applications, AFRICON
- Visualization Techniques for Electrical Grid Smart Metering Data: A Survey, Conf. on Data Computing Services and Applications
- Adaptive Data Collection Mechanisms for Smart Monitoring of Distribution Grids, EDCC

And following journals (some still under way)

- On the trade-off between timeliness and accuracy for low voltage distribution system grid monitoring utilizing smart meter data, International Journal of Electrical Power and Energy Systems
- A Real-Time Open Access Platform Towards Proof of Concept for Smart Grid Applications, Journal of Communication, Navigation, Sensing and Services

Ph.D. dissertations

- Real-time Monitoring of Low Voltage Grids using Adaptive Smart Meter Data Collection, Mohammed Kemal, 2019
- Automation of Smart Grid operations through spatio-temporal data-driven systems, Maria Stefan, 2019

Furthermore, there have been several interviews with the engaged Ph.D. students in local and regional newspapers in relation to this project and their Ph.D. studies that are anchored in the project, see Figure 29 for an example of TME with one of the Ph.D. in the local news. Besides this, internal and external seminars has been used which includes external advisory board meetings, internal board meetings, participation in meetings in e.g. Intelligent Energy. Furthermore, the project has been engaged in setting up workshops such as one related to an IEEE conference in Aalborg, 2018, from where a picture is shown in Figure 30. The workshop lasted a full day, and was overall visited by approx. 20 persons from worldwide during the full day, so conclusion was that it was a great success.

» **Vi begynder at se omridset til noget, der kan blive meget spændende.**

MICHAEL LYHNE, forretningsudvikler hos Thy-Mors Energi

FAKTA

REMOTEGRID

- RemoteGRID er et forskningsprojekt, hvis hovedidé er at gøre gøre data fra "smarte el-målere" tilgængelige for operatørerne.
- Projektet bliver støttet af Energinet.dk gennem ForskEL-programmet, der er finansieret af PSO-afgiften.

Michael Lyhne, forretningsudvikler hos Thy-Mors Energi, sammen med Maria Stefan, en af tre ph.d.-studerende, der arbejder med mulighederne i de "smarte el-målere". Foto: Peter Mørk

Styr på datamængderne

PH.D: Thy-Mors Energi samarbejder med Aalborg Universitet om at bruge de store mængder data fra forbrugernes nye, smarte elmålere

Af Morten Kyndby Holm
morten.kyndby.holm@nordjyske.dk

THY-MORS: De nye el-målere, som alle forbrugere i Thy-Mors Energis område har fået installeret, leverer hver dag en stor mængde data om, hvor meget strøm der bliver brugt på hvilke tidspunkter i elnettet. Og på samme måde kommer der hele tiden en masse information fra de mange producenter af energi til elnettet: Vindmøller, solpaneler og decentrale kraftværker.

I et par år har tre ph-d.-studerende fra Aalborg Universitet arbejdet med et projekt, som skal hjælpe Thy-Mors Energi med at udnytte alle disse data i den daglige drift og planlægning.

Forskningen foregår primært hjemme i Aalborg, på baggrund af data fra Thy-Mors Energi. Men i sidste uge var en af de tre ph.d.-studerende, Maria Stefan, på besøg hos selskabet i Thisted sammen med et hold ingeniørstuderende.

Maria Stefan har i projektet fokus på at skabe overblik over de store datamængder, på en måde så informationerne kan bruges af Thy-Mors Energis medarbejdere.

Det kan i sidste ende blive til glæde for forbrugere, der vil opleve, at elselskabet hurtigt kan lokalisere problemer - og for eksempel se, om et udfald skyldes et usædvanligt højt strømforbrug hos en enkelt forbruger eller skal findes et andet sted i lokalområdet.

Det handler om at få fuldt overblik over nettet:

- De store mængder data skal filtreres, sorteres og visualiseres, fortæller Maria Stefan, der er rumæner, men som valgte at tage sin ingeniøruddannelse i Aalborg. En uddannelse, hun altså nu supplerer med en ph.d.

Thy-Mors Energi har selv budt sig til som samarbejdspartner i forbindelse med ph.d.-projektet - der er interessant for selskabet, dels fordi man var tidligt ude med at udbrede de smarte el-målere, dels på grund af sammensætningen af både producenter og forbrugere.

Projektet løber indtil september 2019, men man regner med at kunne tage resultaterne i brug allerede i år, siger Michael Lyhne, forretningsudvikler hos Thy-Mors Energi.

- Vi begynder at se omridset til noget, der kan blive meget spændende, siger han.

Figure 29: Paper article published in North Jutland

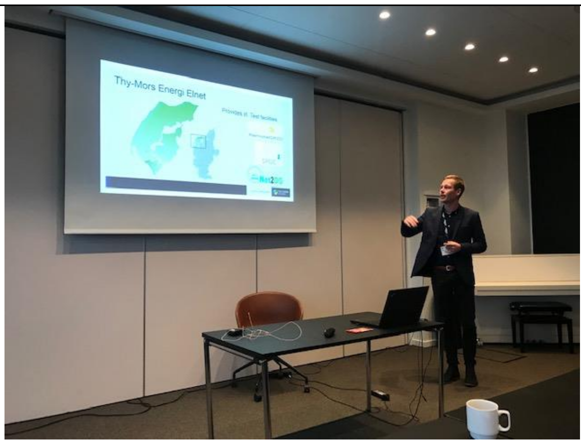

Figure 30: Presentation by Michael Lyhne, TME, at the IEEE SmartGridComm 2018

RemoteGRID also promotes itself via the web, and in Figure 31, the front of the public RemoteGRID website is shown (which has the address www.remotegrid.dk). From there, general information can be found as well as a brief overview of the major news has been pushed here. Locally, each partners have also been using forms of web to disseminate the results, e.g. as seen in Figure 32, TME has pushed an article to their site regarding the final workshop of the project.

Figure 31: Front page of the RemoteGRID web-site

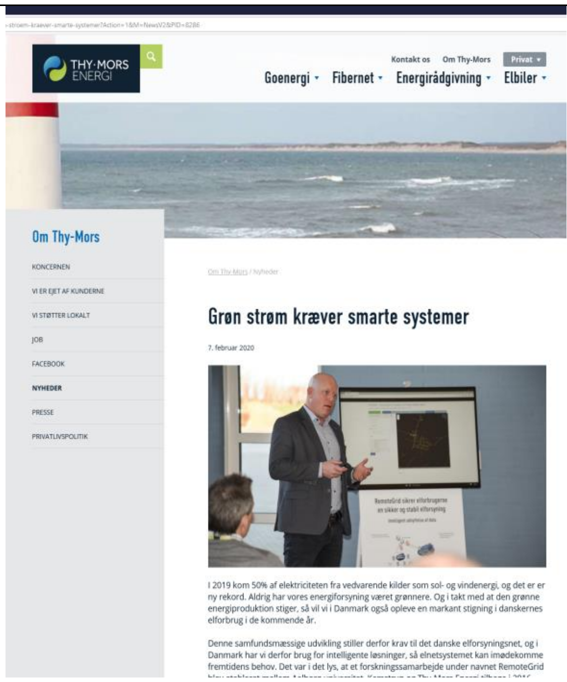

Figure 32: Screenshot of website of Thy-Mors Energy in relation to the final workshop in RemoteGRID

The final workshop was carried out on February 5, 2020 at Thy-Mors Energy, where roughly 20 people attended inclusive the speakers and local attendees. Representatives from EUDP, Dansk Energi as well as other smaller DSO's were present. In overall, that must be considered as a success, as people came from most of Denmark to participate.

1.6 Utilization of project results

Overall, the project has benefitted all parties in the project, and that the fruitful collaboration is planned to continue in further projects is well expected.

Thy-Mors Energi

The exploitation strategy of Thy-Mors Energi is to become aware of the actual potential SM-data provides in terms of grid-operational efficiency, maintenance improvements, and improved assets management towards grid-connected con- and prosumers. The digitization of distribution grids moves from a billing paradigm to an operational improvement paradigm. This transition (could) require a new set of organizational skills/roles within the DSO's. Interacting with state-of-the-art innovators, manufactures and data-analysts provides a unique opportunity to learn and adapt.

Thy-Mors Energi will exploit the knowledge generated within the RemoteGRID project to:

- Promote data-usages in DSO operations.
- Request applications that can generate/produce a desired operational and service level value add.
- Increase intellectual know-how within the organization, to be on the forefront of the digitization of distribution grids.
- Utilize membership in national interest organization to promote legislative changes if necessary.

Kamstrup

With the increased introduction of renewable energy resources into the distribution grid and an escalation of the electrical consumption the demand for flexibility has become a prerequisite. As a technology provider Kamstrup's exploitation goal is enable this flexibility by using the acquired smart meter data. The gain of using the smart meter data will enhance the grid efficiency and thereby its operations. Kamstrup will use the RemoteGRID project and the data provided within to further develop its analytic data platform. This exploitation will provide high-end services and products for the DSO such as improvement of maintenance, fault detections, reduction of down-time, distributed data management and better assets management.

Aalborg University

AAU has produced two Ph.D. projects in the course of the project, and several more scientific publications. The outcomes of these Ph.D.'s leads to several next steps, which can be utilized in further project collaborations and further research jointly with the industry. This is one of the major exploitations that the university plans to pursue.
Additionally, a lot of material and knowledge has been produced that can and will be used in lecturing at master and Ph.D. level. Cases from the project may also be used as low as at bachelor level, while some of the more advanced material will be used at higher level of education. Student projects have been proposed throughout the project, with success, and has led to several collaboration btw. AAU and partners in the project. It is the plan to use the RemoteGRID framework for further enhancing student projects and thereby strengthening the interaction between industry and academia.
Finally, the setup in the laboratory is seen as a key perspective for further utilization, by establishing a training centre for DSO using the real-time framework made available during the project. Furthermore this can be used also as a virtual test facility for smart grid operations and validation of analytics under development.

1.7 Project conclusion and perspective

The project started in a state where DSO's (here specifically Thy-Mors Energi) did not know anything about what is ongoing in their low voltage grid. Based on this, the project put the goal to enlighten the DSO with what is ongoing by utilizing smart meters deployed in the field, and to support with real-time state estimates to ensure a high quality data delivery to the operator. This has been challenged by the low capacity data network in the AMI, which is a generic problem. The solution has been an intelligent interaction between networking components, state estimation and data processing components. But not stopping there, the project aimed to visualize also the huge amount of data in a way to not drown the operator in green flags and other signals.

The first part of the project were focused on using the data and the related use cases, developed in WP1, in which two was clearly defined: 1) *Improved low-voltage grid observability* and 2) *Asset management*. These were the driving cases for assessing the requirements and KPI's for system assessment later on. During the mid-period of the project, the key challenges of a) efficient network access to data, 2) database management, processing and data visualization and 3) real time grid state estimation and asset management functionality was researched. This happened in WP2, WP3 and WP4.

The system deployment that was finally implemented in WP5, as a result of the architecture defined in the early phases of the project, had to be adapted to be in line with security and legal aspects. This has meant introduction of several sub steps, and some additional components not foreseen initially. However, the end result has shown not only legal, secure but also extremely robust, as the field test prototype has been running several months without major issues. The approach to the deployment in the field mean that it was simple to produce a digital twin in the lab of the system, from where failure situation and cyber-attacks could safely be studied.

The overall conclusion of the project is that the developed tools shows that the direction is the right way towards achieving a smarter grid. Several internal feedbacks and discussions among partners and external workshops confirms this. Obviously, there are limitations as would be expected from a proof-of-concept implementation. A later full scale implementation of near Real-Time monitoring, integration of asset management, visualization of system and alarm integration, will reveal the expected potential of the entire concept to become a very powerful tool for improving the DSO's capabilities to operate their existing or future low voltage grids. The developed tools in the project will pave the road ahead for a higher increase and penetration of renewable energy resources in the low voltage grid, or increased support for more electrical vehicles in the low voltage distribution grids.
The RT-HIL framework and associated tools developed for laboratory assessment provides an easy overview of execution and assessment of 'what if' scenarios without having to rely on many applications and dedicated code for visualization and post-processing of results. Obviously, for scientific analysis later on, those are needed, but the tool provides a useful handle of on the spot analysis when doing simulations. Especially, usage of the new tools is beneficial for development and testing of new smart grid functionalities at all levels. Secondly, there is tremendous potential for training and educational purposes, as the tools allows a fairly quick feedback to students or trainees of the physical system in a graphical and more user friendly way.
However, more fundamental research an all areas i.e. data collection, data storage, security, advanced functionalities for monitoring and asset management complemented by demonstrations is needed.

As a final remark, a smart monitoring of the existing low voltage grids, opens further exploitation of the existing capacity in the low voltage grid. This may be a key enabler for future scenarios where more renewable energy resources are envisioned with a high level of electrical vehicles that requires charging, and not to forget the interlinks between electrical energy system and other energy types at the household level will put new requirements to monitoring of the state and asset in that part of the energy supply chain.

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