Funded by the European Union

Project Number:	774145
Project acronym:	Net2DG
Project title:	Leveraging Networked Data for the Digital electricity Grid
Contract type:	H2020-LCE-2017-SGS

Deliverable number:	**D5.3**
Deliverable title:	**Final Consolidated Results**
Work package:	WP5
Due date of deliverable:	M42 – 30/06/2021
Actual submission date:	M42 - 25/06/2021
Start date of project:	01/01/2018
Duration:	42 months
Reviewer(s):	Hans Peter Schwefel, Michael Lyhne
Author/editor:	Florin Iov, Catalin Ciontea, Karthikeyan Nainar, Rasmus Løvenstein Olsen, Kamal Shahid, Yonghao Gui, Christine Schäler, Klaus Strasser, Nuno Silva, Nicola Nostro, Enrico Schiavone, Nicole Diewald, Karsten Handrup, Rolf Kirk, Robert Damböck, Frida Huglen Fredheim
Contributing partners:	Aalborg University (AAU), GridData (GD), Fronius (Fronius), Resiltech (RT), Kamstrup (KAM), Stadtwerke Landau a.d. Isar (StwLan), Thy-Mors Energi (TME), TU Vienna (TUV)

Dissemination Level of this Deliverable:	**PU**

Public	*PU*
Confidential, only for members of the consortium (including the Commission Services)	*CO*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774145. Further information is available at www.net2dg.eu.

The content of this document reflects only the authors' view and the European Commission's European Climate, Infrastructure and Environment Executive Agency (CINEA) is not responsible for any use that may be made of the information it contains.

Statement of Originality

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

Contributors

Part. Nr.	Part. short name	Name of the Contributor	E-mail
01	AAU	Florin Iov Catalin Ciontea Karthikeyan Nainar Rasmus Løvenstein Olsen Kamal Shahid Yonghao Gui	fi@et.aau.dk cic@et.aau.dk kan@et.aau.dk rlo@es.aau.dk ksh@es.aau.dk yg@es.aau.dk
02	TUW	Frida Huglen Fredheim	revheim@eeg.tuwien.ac.at
03	GD	Christine Schäler Klaus Strasser Nuno Silva	schaeler@griddata.eu strasser@griddata.eu nuno.silva@efacec.com
04	RT	Nicola Nostro Enrico Schiavone	nicola.nostro@resiltech.com enrico.schiavone@resiltech.com
05	Fronius	Nicole Diewald	diewald.nicole@fronius.com
06	KAM	Karsten Handrup	kaha@kamstrup.com
07	StwLan	Robert Damböck	Robert.Damboeck@stadtwerke.landau-isar.de
08	TME	Rolf Kirk	rok@thymors.dk

Table of Content

List of Figures

List of Tables

List of Acronyms

Net2DG	Leveraging Networked Data for the Digital electricity Grid
AMI	Advanced Metering Systems
API	Application Programming Interface
AVR	Automatic Voltage Regulation (Net2DG application)
CBA	Cost Benefit Analysis
CCB	Connection Box or Customer Connection Box
CIM	Common Information Model
CSV	Comma Separated Values (file type)
DB	Data Base
DSO	Distribution System Operator
EM	Electrical Measurement
ENS	Energy Not Supplied
GIS	Geographic Information System
GMon	Grid Monitoring (Net2DG application)
GUI	Graphical User Interface
GTS	Grid Topology Subsystem
HE/HES	Head-End/Head-End Subsystem
HTTP	Hyper Text Transfer Protocol
ICT	Information and Communications Technology
ICT-GW	ICT Gateway
IP	Internet Protocol
INV	PV grid Inverter (subsystem)
LAN	Local Area Network
LC	Loss Calculation (Net2DG application)
LV	Low Voltage
MV	Medium Voltage
ODet	Outage Detection (Net2DG application)
ODiag	Outage Diagnosis (Net2DG application)
OGM	Observability Grid Model
OLTC	On-load tap changer
PV	Photovoltaic
PM	Preventive Maintenance (Net2DG application)
PoM	Point of Measurement
REST	Representational State Transfer
RGM	Reference Grid Model
RTU	Remote Terminal Unit
RT-HIL	Real-Time Hardware-in-the-Loop
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SM(s)	Smart Meter(s)
StwLan	Stadtwerke Landau (Net2DG partner)

TCP	Transmission Control Protocol
TME	Thy Mors Energi (Net2DG partner)
VM server	Virtual Meter Server
VMS	Virtual Measurement Subsystem
VSS	Virtual Subsystem
VSS-INV	VSS for PV grid Inverters
XML	Extensible Markup Language (file type)

Executive Summary

This deliverable presents the final consolidated results of the Net2DG project. Starting from the initial targets - 70% reduction of time to outage diagnosis, 10% reduction of LV grid losses, 60% reduction of voltage quality issues, 30% reduction of grid reinforcement costs - the deliverable summarizes the Net2DG approach and relates a set of novel developed applications Grid Monitoring, Loss Calculation, Outage Detection & Diagnosis to these targets. The applications are running on top of a Net2DG developed ICT-Gateway that enables a digital twin of the low voltage distribution grid from the fusion of heterogeneous data sources for grid topology and measurements in the grid. Based on the available integrated and normalized data, calculations of not-measured relevant electrical parameters are performed through an observability grid model which supports a smooth execution of the aforementioned applications and enables a fully digital process for operation and planning of the low voltage grid. In addition, coordinated control of reactive power behaviour of inverters in the low-voltage grid has been realized via the Automatic Voltage Regulation application, which also is executed on top of the ICT-Gateway.

The integrated Net2DG system has been deployed in two field environments, one at Stadtwerke Landau a.d. Isar in Germany, and the second at Thy-Mors-Energi in Denmark. In addition, the technical benefits of the system have been assessed through a real-time Hardware-in-the-Loop laboratory setup at Aalborg University and through extensive offline simulations.

The results from the assessment through the combination of field trial analysis, laboratory setup, and offline analysis showed the following benefits in the scenarios of the German and Danish low-voltage field trial grids: (1) Outage detection and diagnosis time could be reduced to few minutes; (2) Grid losses could be reduced by 11% via voltage management applied in combination with continuous voltage monitoring; when applying a variant of the reactive power coordination of inverters, a reduction by 20% was possible. (3) The hosting capacity of the field trial example grid was increased by 30% through an enhanced planning process using the digital grid status, and an additional 50% increase was achievable through the coordinated reactive power management of the inverters.

Therefore, the results clearly show the benefits of the developed Net2DG solution for the future digital operation and planning of the low-voltage grids and that such digitalization will be a critical contributor to the realization of the energy transition.

1 Introduction

This document is the final deliverable from WP5, with the objective to give an overview of the consolidated results of the Net2DG project.
It was initially foreseen that the Net2DG solutions will allow small and medium-sized DSOs to achieve specific targets as detailed in the following paragraphs.

Reduced time to outage diagnosis
Together with the DSO partners in the consortium, an analysis of the current process for outage detection and diagnosis has been performed. The current process relies on customer voice calls which arrive, possibly in bulks, within some 10 to 120 minutes after the outage (depending on time of day and affected customer types). Mapping to street addresses is either done manually during the call or via the GIS system. The mapping to the LV grid topology is then a subsequent manual step, after which the repair team will be notified and sent out. Coordination for the latter is manual. Automating the process via the data analytics enables a proactive diagnosis and it eliminates a significant part of the manual tasks; based on the estimates in the analysis of the current DSO process, this can lead to a reduction of outage time in the order of 70%.

Reduced LV losses
Energy losses in typical European low-voltage grids today range from 2% to 6%. Optimizing the topology and the power flow in the low-voltage grid in earlier case studies (among them the one from www.smartc2net.eu, though here in MV grid) typically provides a reduction around 10%. As the low-voltage grid also shows some limitations with respect to control of loads and generation and adaptation of topologies, this 10% reduction is put forward as the ambition of Net2DG.

Reduced Number of Voltage Quality Problems:
Currently, the DSOs are not continuously monitoring voltage quality in the distribution grids (only point-wise short-term measurements in case of customers reporting problems). Due to the introduction of renewable generation and due to new consumption patterns, there is a high probability of temporary voltage quality problems. As a first step, the outcome of the project will allow to verify this. An estimate from previous experience is that voltage variations and voltage unbalance will be the majority of the voltage problems, estimated 2/3 of all observed ones. Net2DG has the expectation to be able to address a large fraction the voltage variations and voltage unbalance, leading to the 60% target of reduction (so slightly lower than the 66% attributed to their estimated occurrence).

Reduced investment cost of DER hosting capacity:
Existing studies show a potential for 30% investment deferral by active network management. Net2DG adopts this as a benchmark and therefore sets itself this ambitious value as a target in line with the best cases arising from the state of the art. Reduction of grid investments is provided by Net2DG approach in two ways:

(1) Through a digital twin of the low-voltage grid, the true status of the physical grid is used to detect grid bottlenecks and therefore allows to match grid investments to actual needs in the distribution grid. Therefore a detailed and accurate picture of grid hosting capacity results, which is a major step forward from previously used worst case assumptions.
(2) The hosting capacity of the low-voltage distribution grid is increased in Net2DG by reactive power management of inverters, achieved by control coordination through the DSO based on the digital twin.

The Net2DG tailored solutions implies data fusion from various sources e.g. advanced metering infrastructure, grid inverters, grid topology and the development of dedicated applications on top.

A summary of User Stories elaborated during the first year of the project is presented as these were laying down the foundation for establishing the Net2DG architecture [1] and the definition as well as the development of the Net2DG applications [4]-[6]. The main driver for the applications was found in the DSOs needs to gain observability of low voltage distribution grids by using existing measurement data sources i.e. smart meters, solar PV grid inverters and Remote Terminal Units to firstly monitor the grid, identify operational conditions outside the safe limits and then mitigate their source in a fast and reliable manner. The main applications in scope are Grid Monitoring (GMon), Loss Calculation (LC), Outage Detection (ODet), Outage Diagnosis (ODiag) and Automatic Voltage Regulation (AVR). Additionally, it was found that, for a better integration of these into the DSO control centre, a Graphical User Interface (GUI) is needed to interact with and visualize the output of the applications. All applications were developed to improve the security and reliability of power supply to the end customers and to improve daily operational metrics for DSOs.

The methodology for verification and validation of the developed applications was based on three instruments, each of them with specific characteristics but complementary. Two Field Trials, one located in Denmark and one in Germany, were offered by project partners for demonstration purposes. Additionally, a digital assessment laboratory framework was used for testing and verification purposes under extreme operational scenarios and grid conditions that are seldom occurring in real-life or cannot be replicated on-sites without affecting the customer supply. The document is presenting a brief overview of these instruments highlighting their complementarities and synergies. Using this approach a high confidence level regarding the accuracy, robustness and effectiveness of the developed applications is achieved.

The document is also presenting selected results to demonstrate that the main targets were achieved. Moreover, preliminary recommendations and guidelines for large scale deployments are drawn.

2 Methodology to address targets

This chapter will give an overview of the User Stories and Use Cases using [1], the overall architecture of Net2DG ICT-GW as detailed in [2] and [3], a brief description of applications based on [4], [5] and [6] followed by an overview of the three instruments used for verification and validation.

2.1 User Stories and Use Cases

Based on input from DSO grid scenarios, control aspects and market overviews a set of relevant application oriented User Stories were identified and detailed in [1]. A brief summary of these User Stories is given in Table 1.

Table 1. Relevant User Stories for definition of Net2DG applications

User Story	Description
Post-Outage Diagnostics	As a Customer Service Operator, I want to identify root causes for outage so that my consumers can have their power distribution restored as fast as possible
Preventive maintenance of Low voltage grid assets	As a Customer Service provider, I want to reduce the occurrence rate of future outages so that my connected consumers and prosumers experience fewer outages
Reactive Power Monitoring for grid planning	As a Grid Operator, I want to understand the extent and the causes of reactive power in my distribution grid so that I can reduce the additional stress on grid components and can reduce the amount of over-dimensioning in my grid planning
Voltage quality monitoring and control	As a Grid Operator, I want to reduce over-voltages, under-voltages and voltage dips and swells, so that my connected prosumers operate under an adequate voltage profile at their connection points
Minimize losses in the LV grid	As a Grid Operator, I want to minimize grid losses so that I can reduce my OPEX and my connected prosumers and the regulator perceive me as a green and efficient operator
System Administration and Master Data Management	As a System Administrator, I want to be able to manage the system easily and simple without too much manual configuration and hassle.

These user stories were prepared to define the main functional requirements that are necessary to provide feasible functionalities. Subsequently, Use Cases and the main actors and subsystems required to provide specific solutions were identified in [1]. Based on the analysis, it was evident that measurement data from low voltage grids are required to provide the solutions for all user stories: in some situations as historical and periodically accessed data, in other cases on-demand readings and alarms are required. The source of the data is highly depending on technology rollout. Denmark has already almost 100% roll-out of smart meters while Germany is in the early phases of AMI deployment.

Deployment of Solar PV inverters is very high in Germany while in Denmark it has some reasonable penetration levels in low voltage distribution grids. However, there will be always cases where no measurement device is available and a minimum number of devices may be strategically placed in specific locations in order to achieve a reasonable level of monitoring. Another identified challenge is related to electrical infrastructure. Information regarding grid topology and parameters and customer characterization is very scattered at the moment on various data bases. A large amount of manual work is necessary to gather and corroborate the existing information and make it available in the DSOs' control centre for fast decision processes.
All these findings pointed out to a need for fusion of static and dynamic data from various sources e.g. smart meters, grid inverters, grid topology, parameters, etc. in a systematic and consistent way. Having this common database in place makes it easierto develop applications that are actually addressing the user stories. These applications can be used for planning purposes but also in the running operational day of a distribution grid for monitoring and mitigation actions.
This was the rationale behind the development of Net2DG ICT-Gateway as the data fusion hub and the targeted applications running on top. All initial targets in the project are met by individual or a combination of applications based on specific use cases defined around these targets.

2.2 ICT-GW Data Fusion and Customization

The ICT Gateway is the central point of data collection and where the fusion of data occurs. A generic overview of the ICT Gateway in interaction with a variety of subsystem is illustrated in Figure 1. Details of the gateway and its related functionality and interfaces can be found in [2], [3].
The main principle behind the ICT Gateway is that, through an adaptation layer where data is accessed from various subsystems via dedicated interfaces, the adapters mainly ensure the conversion between different data formats to an internal normalized data object structure. Once data has reached the domain logic layer, various mechanisms exist to ensure correct mapping between measurements and measurement points, validity checks of data, on demand control, data aggregation and fusion and other relevant functionality (see [3] for more details). This allows applications that interact with the gateway to focus on a simple, common interface, with an independent data model of what is used in the variety of subsystems.
The adapter concept also allows to replace the real world interface adapters to those data source interfaces used in the laboratory, where the electrical grid is emulated. In the laboratory setting, subsystems are replaced with Virtual Subsystems (VMS) as described in [6]. Thereby, the main differences between the real world field test deployment and the laboratory setup from the ICT Gateway and application is focused around how data is generated and not how it is processed by the applications. The same version of the ICT Gateway and applications were used systematically through the field test and in the laboratory framework.

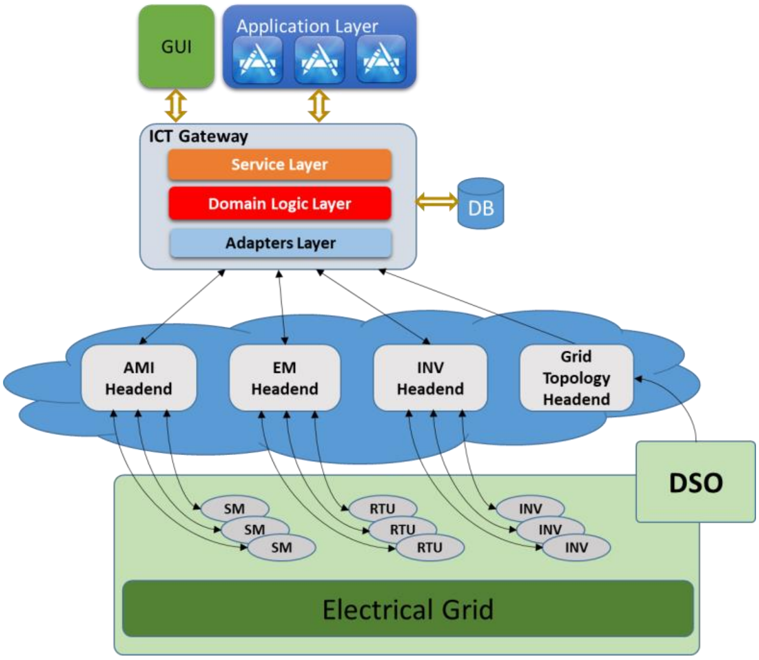

Figure 1: ICT Gateway in interaction with external subsystems

2.3 *Applications*

A brief overview of the applications developed, tested and validated in the Net2DG project is given in the following subsections based on [4] and [6].

2.3.1 GUI

Even if a Graphical User Interface that allows a visualization of grid operational conditions was not initially in scope, it was identified, in the early stages of the project, the necessity of linking the monitoring and control application to the DSO operation control centre and their operators. An intuitive GUI was developed in the project to visualize the network topology and to trigger the applications automatically or on user's request. Depending on the application, the input parameters can be set, and a historical time range selected. After executing an application, the graphic evaluation is opened by clicking on the network elements. In addition, the network elements are marked with a colour scheme to highlight threshold violations.

2.3.2 Observability Grid Model

The Observability Grid Model (OGM) is the critical element in estimating the grid states and algorithms for calculation of various operational variables. Its aim is to increase the distribution grid's observability and describe a numerical method for solving non-linear problems. The normal state in the electrical grid is calculated by obtaining complete voltage information for each node and determines active and reactive power flow in each branch. The OGM is an integrated model, and applications for the voltage analysis, loading analysis or loss calculation utilize its functionality. The DSO is enabled to observe the grid and gains additional information, leading to higher efficiency in grid planning and operation.

2.3.3 Grid Monitoring (GMon)

The Grid Monitoring (GMon) application allows the end user, i.e. the DSO's control centre operator, to specify a given time interval in the past and then visualize through the GUI application a set of operational variables in all electrical nodes of the low voltage grid as:

- average voltages for the given time interval;
- time stamps where the average voltages exceed the configurable threshold;
- frequency of occurrence for over- and under-voltages;
- evolution over given time interval of the 95% and 5% quantiles of the average voltages, as specified by power quality standards e.g. [14], over a one-week sliding-window.

GMon can either use measured voltages, or voltages estimated by OGM.

2.3.4 Outage Detection (ODet)

The Outage Detection (ODet) application identifies and notify when an outage occurs in the distribution grid. It is triggered: i) by an under-voltage event; ii) by a communication outage or iii) manually by the DSO's personnel in control centre. Upon this trigger, it provides, through the GUI, the set of nodes (customers or grid internal nodes) that are affected by the outage.

2.3.5 Outage Diagnosis (ODiag)

The Outage Diagnosis (ODiag) application allows to determine and localize the cause of an outage. This application, which is triggered by the detection event of the ODet Application, is requesting additional measurements i.e. 1 second values of voltages, and in case of the substation measurements also currents, from the ICT Gateway. The location and behaviour of the fault is assessed by a combination of processing data gathered from reachable measurement devices and deploying methods for short-circuit impedance calculation. The following outputs provided by ODiag is available via GUI to the DSO's operator:

- a list of grid locations (substation, cables, junction boxes) and the likelihood that the cause of the outage is associated with these grid locations;
- timestamp at which the fault started to become active;
- location of the fuse that has been burnt (if any) as consequence of the short-circuit fault.

2.3.6 Loss Calculation (LC)

Loss Calculation (LC) application allows the DSO operator to specify a time interval in the past and then uses measured average active and reactive energy values to provide through the GUI:

- active and reactive power profiles on the secondary (low voltage) side of the transformer;
- absolute and relative active power total loss for the entire monitored low voltage grid;
- reactive power contribution of the cables in the grid.

2.3.7 Automatic Voltage Regulation (AVR)

The Automatic Voltage Regulation (AVR) manages the coordinated voltage control of the solar PV inverters connected into the monitored LV distribution network in order to achieve:

- o fair distribution of inverters' reactive power support to counteract over-voltage due to multiple generators along feeder, including solar inverters themselves, thus maximizing DER hosting capacity without grid reinforcement;
- o reactive power balancing of LV grid behind a secondary substation to prevent transformer overloading; it will be shown later that such reactive power balancing can also reduce grid losses.

2.4 Verification and Validation Instruments

The Net2DG project uses a combination of field trials located at Thy-Mors Energi (TME) and Stadtwerke Landau (StwLan) premises and a digital assessment framework to extensively verify and validate the developed applications. The digital assessment framework consists of an off-line simulation environment complemented with a Real-Time Hardware-In-the-Loop system. This approach allows a great deal of complementarity and synergies to be created in order to achieve good insights into the results obtained and how they relate to the Net2DG targets. Table 2**Fejl! Henvisningskilde ikke fundet.** gives an overview of the complementarities and synergies for the various instruments used by the Net2DG project to verify and validate the developed applications. Relevant results from field trials and digital assessment framework are provided as inputs to Cost Benefit Analysis (CBA).
A brief overview of these instruments is given in the next subsections

Table 2. Overview of complementarities and synergies of various instruments used in Net2DG

	Complementarities	**Synergies**
TME Field Trial	➢ Interoperability with AMI and SolarWeb head-end systems ➢ Validation of software under realistic conditions	➢ Provides data input and configuration parameters for digital assessment framework ➢ Scenario with measurements at customer site (Smart Meters)
StwLan Field Trial	➢ Interoperability with SolarWeb and RTU head-end systems ➢ Validation of software under realistic conditions	➢ Provides data input and configuration parameters for laboratory and offline studies ➢ Scenario with measurements at junction boxes
Digital Assessment Framework	➢ Validation of software under extreme operational scenarios ➢ Extensive sensitivity analysis ➢ Repetitive tests for statistical analysis of application performance	➢ Allows sensitivity analysis for erroneous data, e.g. wrong grid topology information ➢ Provides guidelines for field test executions ➢ Provides additional data for statistical analysis and confidences for results

2.4.1 TME Field Trial

This field trial is located in North-Western Denmark and consists of a complete secondary substation providing power supply to a small village. There are 98 customers (household, small industry, public institutions, supermarket, etc.) connected to five low voltage feeders as shown in Figure 2. There are several roof-top solar PV installations and there is a 100% roll-out of smart meters.

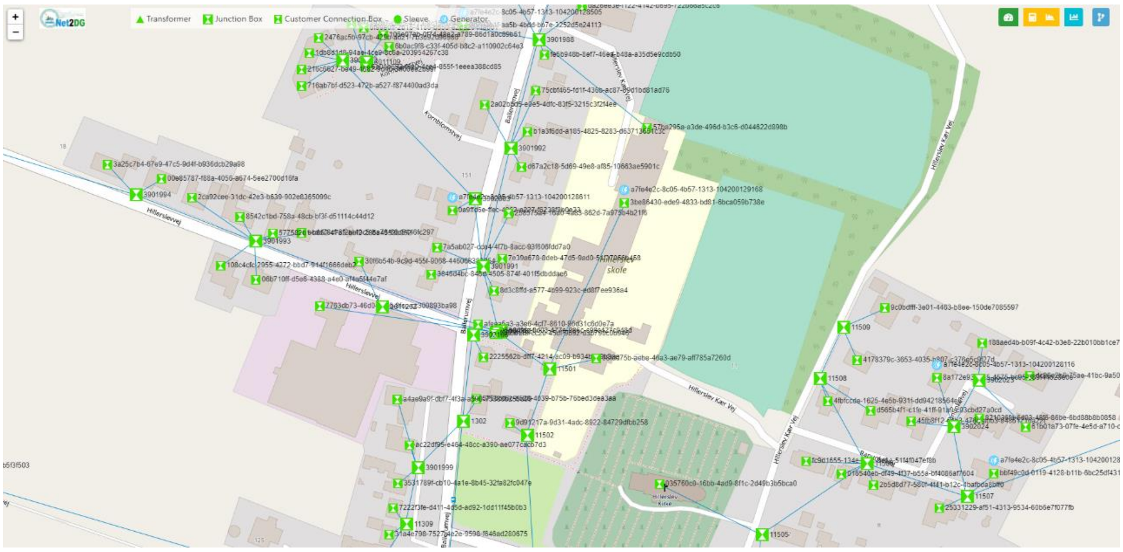

Figure 2. GUI overview of TME Field Trial.

The mixture of different types of loads and its location nearby the TME control centre was making it very suitable for Net2DG purposes for validating three applications namely GMon, LC, and ODet using the interoperability with AMI and Solar Web.

The Net2DG solution was installed as a cloud solution with access to the relevant TME topology and measurement data, however challenges occurred during the process. A new data concentrator for Smart Meters was installed in order to achieve a complete decoupling of Net2DG system from the actual AMI production system. Thus, verification and validation of applications were not interfering with the normal data collection mechanisms. Another challenge was related to the integration of ICT-Gateway to the alarm and event handling server that was not part of Kamstrup Head-End system but operated by a joint association of DSOs. A limited connection and access to mainly historical data from this system was achieved. However, the functionalities of Net2DG's applications were fully demonstrated.

2.4.2 StwLan Field Trial

This field trial located in Northern Bavaria brings another relevant case to the Net2DG project. The site is also a complete rural secondary substation having 73 customers representing households and small commercial businesses. There are 22 roof-top solar PV systems with a total capacity of 219.44 kWp and no deployment of smart meters. Moreover, StwLan has no monitoring of this low voltage distribution system.

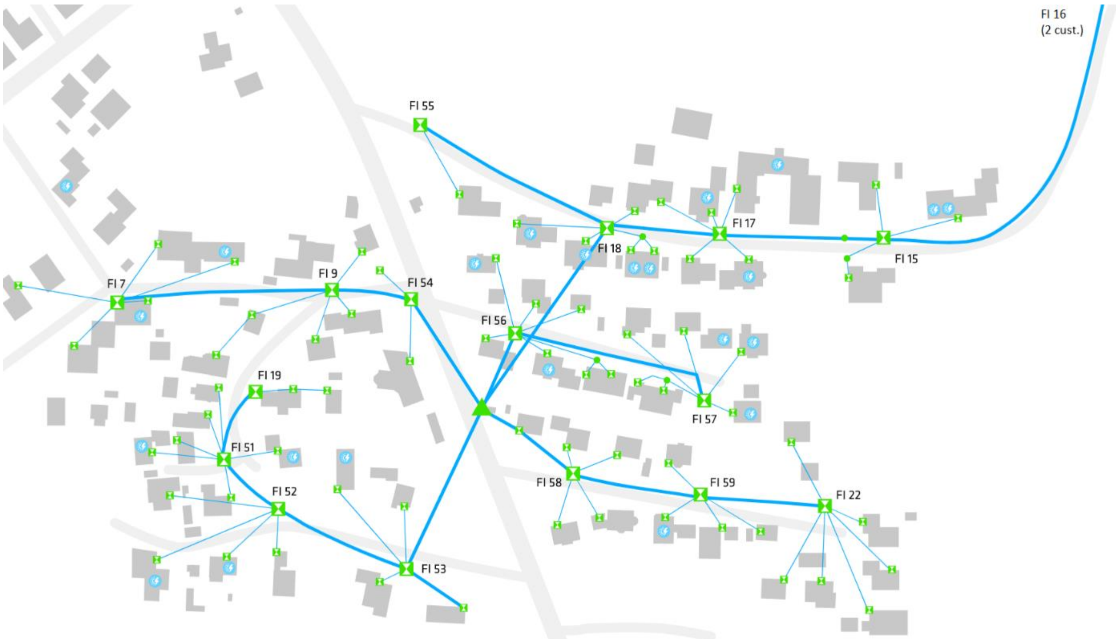

Figure 3. GUI overview of StwLan Field Trial.

In this case the Net2DG project was focusing on the interoperability of the ICT-Gateway with solar PV inverter and Electrical Measurement (EM) devices connected by Remote Terminals Units (RTU) installed in selected junction boxes along the low voltage feeders. Thus, several RTUs were installed in the field trial and connected to ICT-Gateway besides the full connectivity to the Fronius' SolarWeb Head-End. Two applications namely GMon and Grid Planning based on the Digital Twin were tested and validated on this field trial. Moreover, extensive studies related to increasing capacity of solar PV systems were conducted as part of grid planning studies and furthermore initial tests of the Net2DG solution on a Medium-Voltage feeder were performed.

2.4.3 Digital Assessment Framework

The laboratory digital assessment framework was focusing on two approaches namely on the integration of the ICT-Gateway into a complete cyber-physical systems running in real-time and the development of an off-line simulation framework using relevant functionalities and proprieties of the real system, see e.g. [10], [11].

This system is centred on a Real Time Discrete Simulator where distribution grid, customers and the measurement points are captured in a configurable model. Several models and tools have been developed and tested to allow flexible integration of ICT-Gateway in a realistic closed to real life way. An overview of ICT-Gateway deployment in this framework according to Smart Grid Architecture Model (SGAM) [15] is given in Figure 4.

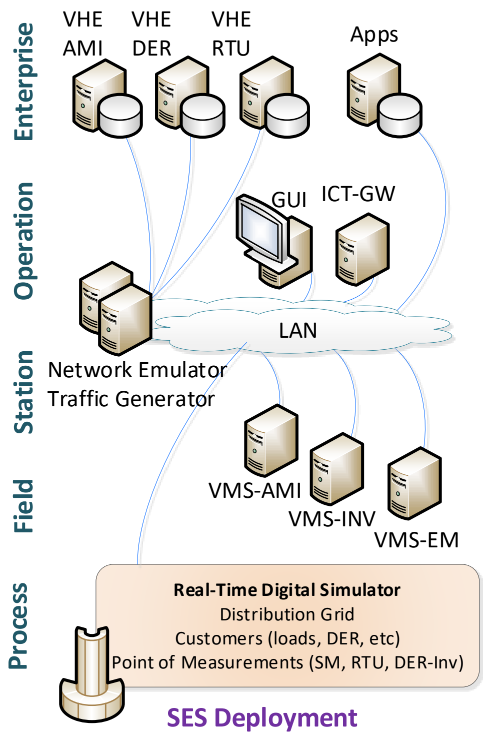

Figure 4. Deployment of ICT-Gateway in laboratory RT-HIL Framework

The distribution grid model is based on the TME Field Trial and modified accordingly to support various operational scenarios e.g. increased penetration of solar PV, outages in selected locations.
The AMI infrastructure from smart meter to head end system is using virtual models for smart meter, data collection mechanism and the head-end system including data bases. A similar approach is used to capture the SolarWeb system and the Head-End server that connects to RTUs. In particular the Solar Web emulator is capturing the bidirectional data flow from Inverter to AVR app via Head-End and ICT-Gateway and back to a specific inverter according to generated references by AVR.
A dedicated platform is used to emulate specific communication networks and their data traffic characteristics using traced based measurements from real systems. This framework allows basically two types of approaches in Net2DG project namely a decoupled open loop system and a closed loop one.

Open-loop operation: The RTDS system is used in the Open-Loop approach for off-line simulation studies or to fast generate variables in all point-of-measurements in the distribution grid as shown in Figure 5. Typically, a 24 hours simulation time window with one second resolution of data inputs will generate the raw data in all measurement points in approximatively 15 minutes.

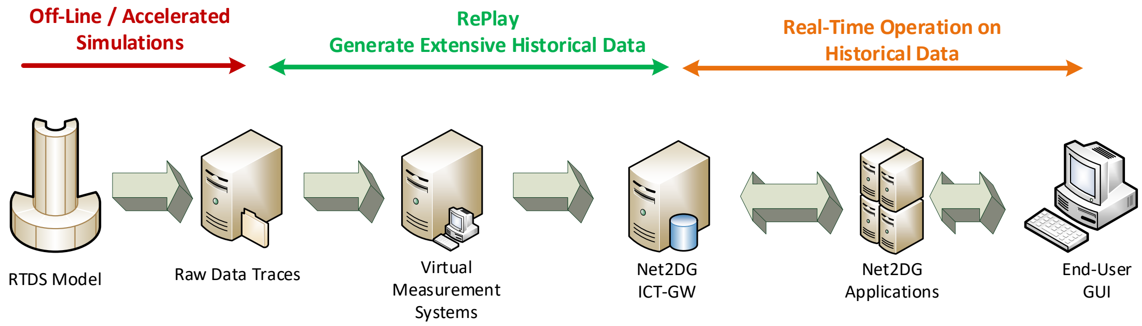

Figure 5. Open-Loop utilization of RT-HIL framework

The Virtual Measurement Systems (VMS) is basically emulating smart meters, measurements from grid inverters or an RTU equipped with a specific functionality to export at runtime the data stream from any source that feeds in data to the VMS. Typically, this source is the Grid Simulator in the laboratory. An internal double buffering mechanism is developed to ensure that the VMS is able to perform and write operations on the disc while still receiving data, hereby allowing long term executions not limited by memory of the device. The VMS is then able to replay the recorded data, so that it mimics the RTDS. For applications that do not require direct interaction with the grid such as AVR application, this speeds up greatly the analysis where statistic results are critical, e.g. sensitivity analysis with respect to delays. However, all the Real-Time operation of Net2DG applications that are using historical data, i.e. GMon, LC, ODet and ODiag are not affected. The main advantage of this approach is that multiple operational scenarios, test cases including sensitivity analysis can be quickly studied.

Closed-loop operation: The second approach is involving a closed loop of all subsystems and it is suitable for verification and validation of applications that require actions from grid connected assets. A schematic representation of this approach is shown in Figure 6. This is the case of the AVR application that requires periodic measurements from the grid in order to generate individual references for solar PV inverters.

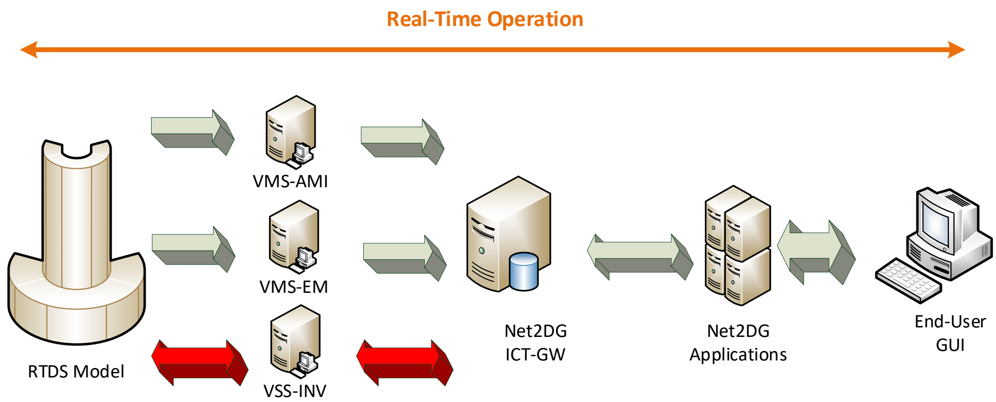

Figure 6. Closed-Loop utilization of RT-HIL Framework

2.4.4 Cost-Benefit Analysis

The cost benefit analysis (CBA) evaluates the potential financial benefits and costs savings, as well as the costs, related to implementing the Net2DG solution. Benefits such as reduced outage detection and outage diagnosis time, loss reduction, increased hosting capacity and potential deferral of investments were evaluated and monetized in the CBA.

The potential time reductions achieved by implementing the Net2DG application were calculated as part of Work Package 6 in the Net2DG project.

Outage Management – ODet and ODiag improvements

Based on input from TME, StwLan and GD the maximum time benefits achieved through Net2DG implementation were quantified and compared. Based on the results, it was identified that a higher time reduction potential in outage management can be achieved in a digitalized distribution grid. Nonetheless, the significant time reductions in outage detection and outage diagnosis results in financial benefits in regard to the cost of energy not supplied for both DSOs. Furthermore, savings in personnel costs can be achieved, as DSOs with the Net2DG solution implemented are able to provide technicians with accurate information regarding fault location and cause, thus significantly reducing the searching-time. An additional benefit is the reduction of SAIDI, as the duration of outages is decreased. The improved accuracy of fault detection also leads to several qualitative benefits, such as improved SAIFI values and improved availability of network assets.

Operational efficiency - Loss reduction and Grid Monitoring

Utilization of the Net2DG solution, initiated by Loss Calculation (LC) application, results in loss reductions, as proven later in section 3.2 - 3.4. The financial benefit of loss reduction, i.e. the monetary savings achieved by the DSOs, were calculated for both TME and StwLan using the average day-ahead price for electricity. The advanced accessibility of smart grid data for the DSOs can lead to deferral of grid investments, as increased knowledge regarding grid assets and more accurate loss calculations provide a better basis for grid planning and adjustments. By implementing the Net2DG solution, DSOs will gain better accessibility to data and thus the accuracy of grid analyses will improve. Using information provided by the DSOs regarding grid assets, combined with information regarding required grid reinforcement, the monetary benefit of deferred investments was calculated for an exemplary secondary substation. The increase in hosting capacity, made possible with the implemented Net2DG solution, was monetized depending on the amount of data availability in the grid.

3 Summary of Achievements

This chapter is presenting an overview of selected results and achievements against the Net2DG targets.

3.1 *Reduced time to outage diagnosis*

An outage in the grid results in customers not supplied with energy, and therefore has to be avoided. With Net2DG, we reduced the time to outage diagnosis drastically. In this section, the use case serving as baseline to assess the proposed solution and required system functionalities to address this target is presented. Since a full-featured validation of Odet and ODiag is not possible on field trials due to technical limitations, a relevant digital assessment study serving as a proof-of-concept of a successful implementation is shown. However, assessing the outage time reduction is only meaningful in the field. Consequently, results of the field trial supporting the targeted outage time reductions are presented. Finally, practical challenges for large scale deployment of Net2DG outage diagnosis solution and respective solutions are discussed.

3.1.1 Use Case Description

Before Net2DG, the DSO must detect and diagnose an outage semi-manually. Figure 7 illustrates the respective process from the DSO perspective. It consists of three phases:

A. Detection: become aware of the outage and find out which grid nodes and customers are affected
B. Diagnosis: find the cause of the outage and localize the cause in the grid – focus here is on short-circuit faults
C. Repair the outage.

Outage detection is usually done by the DSO getting a call from a customer, which notices the outage; the duration until the customer calls can vary strongly – from few minutes during daytime in populated buildings to hours or even days, when no humans are present in any of the affected buildings. The set of affected customers is subsequently determined by a manual or digitally assisted process. For outage diagnosis, staff members drive to the respective location and try to find the cause of the outage. Afterwards, they repair the outage on side. Therefore, the time for detection and diagnosis will vary significantly while the time to repair the outage highly depends on its cause and the time to reach the faulted location in the distribution grid by the repair team.
The time for outage detection and diagnosis can be substantially reduced with the Net2DG solution. To this end, first, the Net2DG solution has to notice the outage as soon as possible after the outage happened. This is usually done when a measurement device sends a respective under-voltage or outage alarm, and happens far before a customer calls the DSO. This requires respective alarm handling of the Net2DG solution. Second, to find the grid nodes affected by the outage, the Net2DG solution analyses grid topology and received measurement data and performs on-demand access for checking which measurement devices still work and provide valid voltage values. This step is performed by the ODet application, using the respective topology and measurement data from the

ICT-GW. This all happens fully automatized as a background process. As soon as ODet finishes, the GUI then visualizes which nodes are affected by the outage. Thirdly, ODet triggers the ODiag application which analyses the outage and provides via the GUI information regarding what needs to be repaired. In total, Net2DG allows to diagnose outages before a customer calls the DSO, reducing the overall time of the outage and hence, the Energy Not Supplied (ENS), and the reliability indices SAIDI.

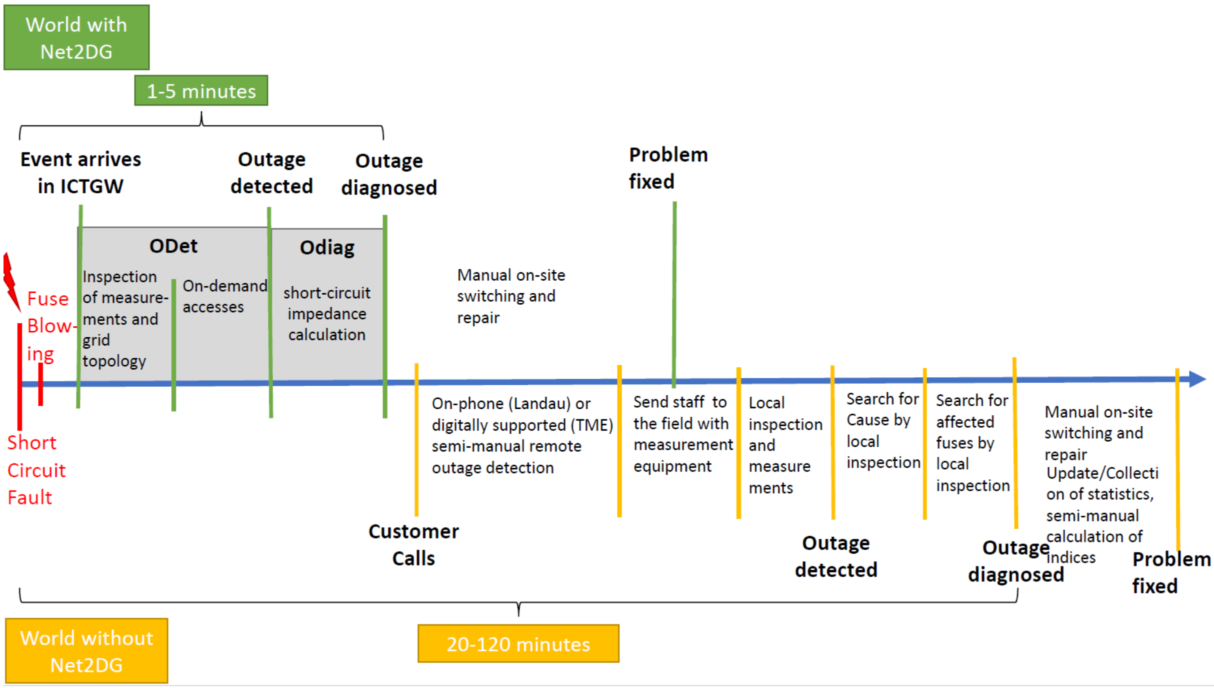

Figure 7: Outage detection and diagnosis with and without Net2DG.

3.1.2 Digital Assessment Studies

Due to technical limitations in the field trials, Net2DG team reached a proof-of-concept solution by using the digital assessment framework. Since ODet and ODiag runs online using historical data (as it is the case for the other applications), validating them in an online fashion is essential. Consequently, the framework described in Section 2.4.1 including the Replayer and the VMS in real-time mode was used. A respective run of this proof-of-concept implementation is illustrated in Figure 8. Based on the output files from the RTDS simulator, the VMS sends periodical measurements and alarms in real time to the ICT-GW. As soon as an alarm relevant for ODet arises, i.e. an undervoltage alarm, the ICT-GW publishes this alarm on a message bus. ODet receives this alarm instantly and starts processing its algorithm as explained in Section 2.3.4. During this algorithm, it performs asynchronous on-demand requests trough the ICT-GW. Based on a configurable waiting time, it requests the last measurement of the devices of interest. Experiments prove that the ODet algorithm detects reliably the areas in the LV grid that are in outage, which was caused in the lab experiment by a switch opening or a metallic short-curcuit fault. The processing time for the ODet algorithm is in miliseconds range in the considered case when using of-the-shelf hardware. However, the processing time depends on the size of the monitored LV distribution grid area behind the secondary substation. Figure 8 clearly indicates that the time to outage detection is determined by the event delay and time for on-demand request, that have to be configured for every digital assessment study.

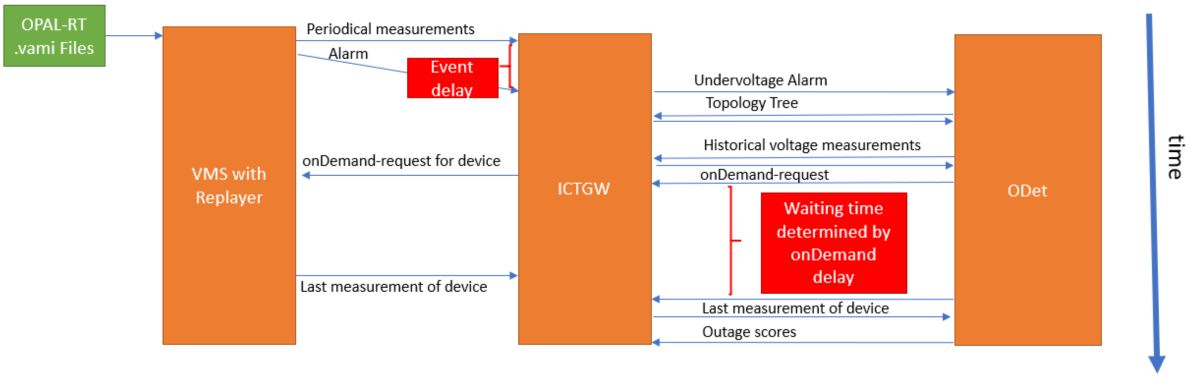

Figure 8. Setting of digital assessment study for outage time reduction target.

3.1.3 Field Trial Results

Net2DG reduces time to outage diagnosis by reducing time to detection with ODet, and time from detection to diagnosis with ODiag. Beside the runtime of these applications from an algorithmic point of view, the run time is dominated by the time until the event reaches the ICT-GW, and the time needed for on-demand accesses. To get insights on these timings in the field, two studies on TME field trial as outlined below were performed.

3.1.3.1 Event delays

The mechanism of the experiment for studying the event delays is illustrated in Figure 9. The methodology and results of this experiment are presented as follow. A customer in TME field was selected and the alarm delays upon disconnecting certain phases were measured. First, phase 2 was disconnected to get insights on the alarm behaviour of the AMI system upon the single-phase outage. Afterwards, the phase was reconnected to give the grid time to recover. Then, a three-phase outage was emulated by disconnecting in sequence phase 1 then phase 2 and 3. It shall be noticed that simultaneously disconnecting all three phases is not possible as each of the three phases has to be detached separately by manual intervention. Upon disconnecting phase 2, an undervoltage push alarm was received after 12.58 seconds. An alarm after disconnecting all three phases in sequence was not received, however a log entry is available. Furthermore, a power fail – alarm was received in the technical portal in 24 seconds after reconnecting all phases. The rationale is that the SM was switched off due to the three-phase outage, and was therefore not able to send the alarm out. Thus, it was concluded that typically an alarm is received within 10 to 20 seconds in the technical portal. This also means that ICT-GW will receive the alarm in this very short time range. It is also essential to give the DSO the ability to trigger ODet manually from the GUI, for instance in order to identify a correctly operational grid after a customer call that was reporting an outage caused actually behind the meter on the customer premises e.g. a blown fuses on the customer electrical switchboard.

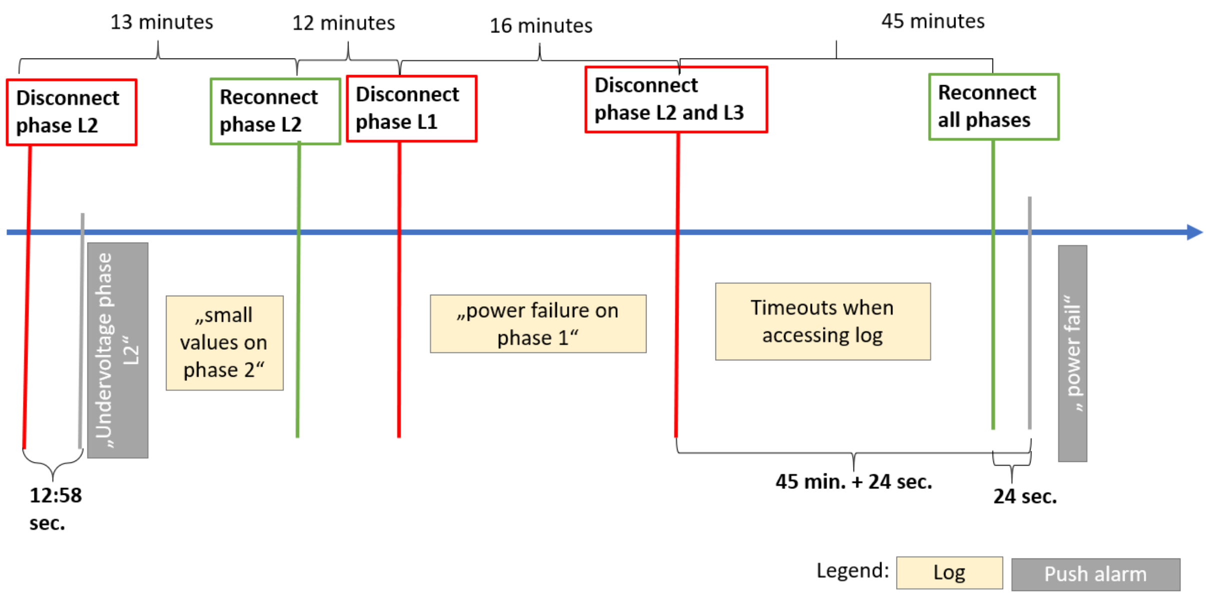

Figure 9. TME field trial study regarding event delays.

3.1.3.2 On-Demand Measurement

The on-demand measurement targets to assess the time it generally takes for measurements to be executed at application level when being called on-demand. This time is influenced by the communication technology and by the communication network topology. The intention of this analysis is to obtain reasonable numbers for the triggering of a reading until response can be expected. The communication topology of the AMI was analysed, and in general one or two hops over intermediate meters are to be expected for request/response. The requests can be done either individually with one meter or in bulks with N meters. Both methods were tested in the field trial. It has been found that the typical reading time is about one minute with some requests towards two minutes. There was one request, which in the experiment was the very first request to read the meters, which took nearly 10 minutes; here further investigation is needed in order to understand the causes of variability of the response time.

3.1.3.3 Summary and Discussion

The time to outage detection is mainly determined by the event time delays and the on-demand access time. The field trial results indicate firstly that, if the Smart Meter is able to communicate (i.e., no total failure) the time for event delays can be assessed with 13 seconds. Second, if one avoids occasionally occurring large access times, the results indicate that the time for further on-demand accesses is nearly independent of the number of accesses, and e.g., less than 3.5 seconds for eight parallel accesses. As a result, the time for the data acquisition for the outage detection is 16.5 seconds in the TME deployment scenario of Smart Meters connected via a wireless meshed network.

Significant reductions of outage detection time and outage diagnosis time were achieved when applying the Net2DG solution. After close evaluation and inspection of the various processual steps in collaboration with the two DSOs, the time reduction benefit was found to amount to approximately 2 hours and 20 minutes for StwLan in a manual process and 1 hour and 30 minutes for TME in a digitally assisted process. As the current StwLan grid is considered less digital than the current TME grid, a higher time reduction potential is achieved. Utilizing this time reduction benefit, combined with information provided by the DSOs, financial benefits in regard to the cost of energy not supplied was found to be approximately 15,000 EUR for TME and 470 EUR for StwLan under the given assumptions. Another potential benefit of reducing the outage detection and outage diagnosis time is savings in personnel costs. It was found that around 50 EUR/outage can be saved for StwLan and 59 EUR/outage can be saved for TME. Based on information provided regarding the average annual number of outages in the low voltage grid, the annual savings in personnel costs were calculated to be 483 EUR for StwL and 3,422 for TME. In order to increase the accuracy of these values, more accurate information is required regarding number of personnel contributing per outage and number of outages occurring in the low voltage grid per year. Furthermore, such values strongly depend on the number of LV grid outages that occur in the distribution grid and on future regulatory awards for reduced SAIDI.

3.1.4 Challenges for Large Scale Deployment

The reduced time to outage diagnosis objective is addressed by the two application ODet and ODiag. The current ODiag implementation relies on substation measurements, which in most cases including the Danish field trial case, are faster to obtain. The wireless multi-hop network that connects to the customer Smart Meters does not need to be used for this substation measurement access in the TME system. Thus, ODiag’s performance relies mostly on the round-trip time delay of the communication link to the substation measurement device.

There are several challenges with the ODet functionality in that it depends on: 1) an alarm signal to be sent and 2) on-demand access to meter readings. The integration necessary to receive the alarms automatically, requires at this stage involvement and integration with another IT system of a third party, which was not done in the course of the project. The on-demand access to meter readings for the AMI system was implemented, but further maturity and testing of this component is required for a reliable and safe reading. There is a high level of security around access to the meter data from the AMI, and several security mechanisms inclusive non-technical ones, that must be implemented. However, while the AMI in the Danish case is the major source of data for outage detection, Electrical Measurements connected by RTUs and PV units will also provide useful input and interfaces that serve as sources for alarms and on-demand readings. Here, the timing for alarm generation and on-demand readings for RTUs is expected to be in the order of a few seconds for a cellular connection to the RTU; the current alarm forwarding implemented by the inverters and the inverter portal however is leading to longer delays; the near real-time provisioning of alarms by the inverter systems may be an interesting feature for future investigation.

Thus, the benefit of the ICT-GW which implements a generally applicable approach for access to the relevant data becomes clear, as the ODiag and ODet does not care from which source the alarms or readings are from as long they are correctly mapped and valid in time. Enabling the two applications by alarms also ensures scalability, as processing time for both is focused only to relevant grid locations at relevant time, and does not otherwise consume processing power.

Alarms and on-demand measurements can only be received by the Net2DG solution in case the measurement device and the communication network are operational. In case of three-phase outages, there can be an improvement of the response time from the so-called Last Gasp function of measurement devices, i.e. that the device is still able to communicate an alarm through short-time local power supply. In case of short-circuit faults causing the outage, there are however also neighbouring measurement devices that will see a voltage drop without a subsequent outage. These neighbouring measurement devices can therefore also issue the initial alarm. A detailed analysis of the improvement of Last Gasp functionality as opposed to utilizing alarms from neighbouring measurement devices will be interesting as future study.

The outage detection will also work in case of only partial measurement device deployment, e.g. 20% Smart Meter deployment as it may result from the current regulatory local requirements in several European countries. However, the accuracy of the Outage detection being able to identify the accurate set of customers may suffer. Strategic placement of additional measurement devices in selected junction boxes will lead to an improvement and should be studied for the specific grid scenarios. Such a study is already facilitated in an offline fashion by the Net2DG system, as it anyways builds up a digital twin of the grid. An online application usable by the DSO directly could be a future step forward.

3.2 Reduced LV losses

3.2.1 Use Case Description

The first step in reducing losses in a low voltage grid is to determine them accurately. Most DSOs today only make a yearly estimation of the total losses in the distribution grid from the energy measurement at the handover point to the higher layer and from consumption/generation billing data. One method to estimate the low voltage grid losses by a DSOs with 100% smart meter rollout and deployed substation measurements is to subtract from substation level measurements the energy values from the customer smart meters. This, however, involves a lot of manual steps in order to assure the correct sets of customer measurements being associated with the right substation measurement. Net2DG in this case was relying on a full estimation of grid losses using customer measurements or alternatively the OGM. Actions to reduce losses may use the following approaches:

1) AVR application or a set of rules for setting up grid inverters in order to reduce losses based on reactive power management.
2) adjustment of tap changers of secondary substations to change the voltage levels in the LV grid.
3) Adjustments of low-voltage grid topologies utilizing existing manual switching opportunities. Among the two field trials in Net2DG, LV grid topology adjustments were only feasible in the StwLan field trial grid. Therefore, the assessment of loss minimization focused on reactive power management and voltage management.

3.2.2 Digital Assessment Studies

First, the effect of the voltage on the losses is examined. For this purpose, different values of voltage on the secondary side of the transformer were considered for Feeder 5 in the TME grid. The result of the OGM calculation for this realistic LV grid feeder and the subsequent loss calculation shows that a 5% reduction of the transformer voltage from its rated value is increasing the losses with 12 %. An increase in the voltage by 6%, on the other hand, leads to an 11.6% reduction oftechnical losses. This analysis assumes that the power values of the loads are not affected by the changes of voltage. However, the results may be different when other types of loads are considered, e.g. constant current or voltage dependant. The voltage on the secondary side of the transformer can be changed by adjusting the tap changer. However, the adjustments of voltages via manual tap changers do require careful considerations of the grid behaviour as those should not lead to voltage violations. Therefore, a grid monitoring must be in place and the voltage profile should be systematically observed.

Another case study is carried out using a variant of the AVR app controlling solar PV system in a LV feeder; this AVR variant has been modified to the objective to minimize the reactive power at the substation via the reactive power behavior of the inverters. In this case, in order to check the loss minimization effect by using the modified AVR app, we take an example high load operation condition from the field test, the Power values at the substation are P=35.45 kW & Q=25.74 kVar. When we only assume Feeder 5 to be present, the total power loss within Feeder 5 without the AVR app is 0.95 kW. However, when the modified AVR application is running the total power loss in the system is decreased to 0.76 kW, which is a 19.8% reduction.

Table 3 summarizes the findings on technical losses by the variation of the voltage level and the applied automated voltage regulation. The change from the rated line-to-line voltage of 400 V has a direct effect on the grid losses. The voltage monitoring ensures compliance with the voltage limits in the overall network. The modified AVR application was executed in a second step using a high load hour: the reduction in losses using the AVR application during this high-load hour is about 20%. The results shown obviously depend on the specific LV grid and on the load and generation scenario in this LV grid. They have been obtained for one realistic setting from the field test, showing the potential of these loss reduction methods. A detailed specific analysis for other grids can be executed automatically based on the digital twin built by the Net2DG solution.

Table 3. Technical losses for different line-to-line voltage levels on secondary side of substation transformer

Control Method	Transformer voltage [V]	Technical Loss	Delta losses [%]
Tap-Changer	380	1.05 kWh/day	+12.0 %
	400 (base case)	0.93 kWh/day	Base Case 1 typical daily load
	424	0.83 kWh/day	-11.6 %
PV Inverter with Standard Q(U) local control	400	0.95kWh/hour	Base Case 2 – high load peak hour

PV Inverter with Reactive power minimization at substation level strategy	400	0.72 KWh/hour	-19.8 %

The goal of Net2DG is to reduce network losses in the LV grid by 10%. This has been exceeded with the results presented above. The basis for reducing losses is the ability to analyse and control the power distribution grid. In the case of manually adjusting the transformer voltage, a systematic monitoring process should be in place. By having the AVR application in place, a fully automated control of the voltage profiles along the feeders can be achieved by using solar PV systems. Thus, a significant reduction up to 20 % of technical losses is achieved in this specific study case.

3.2.3 Field Trial Results

The LC application was executed using four days of measurement data from customer Smart Meters and from the substation meter in TME field trial in early March 2021. Partial results of the application as presented in the GUI are shown in Figure 10. The grid losses are shown relative to the substation energy and these relative losses per 15-min interval vary strongly, revealing a peak of about 15%. The average relative loss over these 4 days (figure also provided by the LC application, but not shown here) result in 6% loss. Peaks with high relative losses can in principle result when the energy exchange with the medium voltage grid in the substation is close to zero. This is a typical scenario when distributed generation is almost balancing the consumption into the LV grid. However, this is not the case in this setting, as consumption is always dominating. The detailed diagnosis of such high losses scenarios can be supported by the Net2DG system by analysing the reactive power including the cable contributions. However, such detailed diagnosis is beyond the purpose of this document.

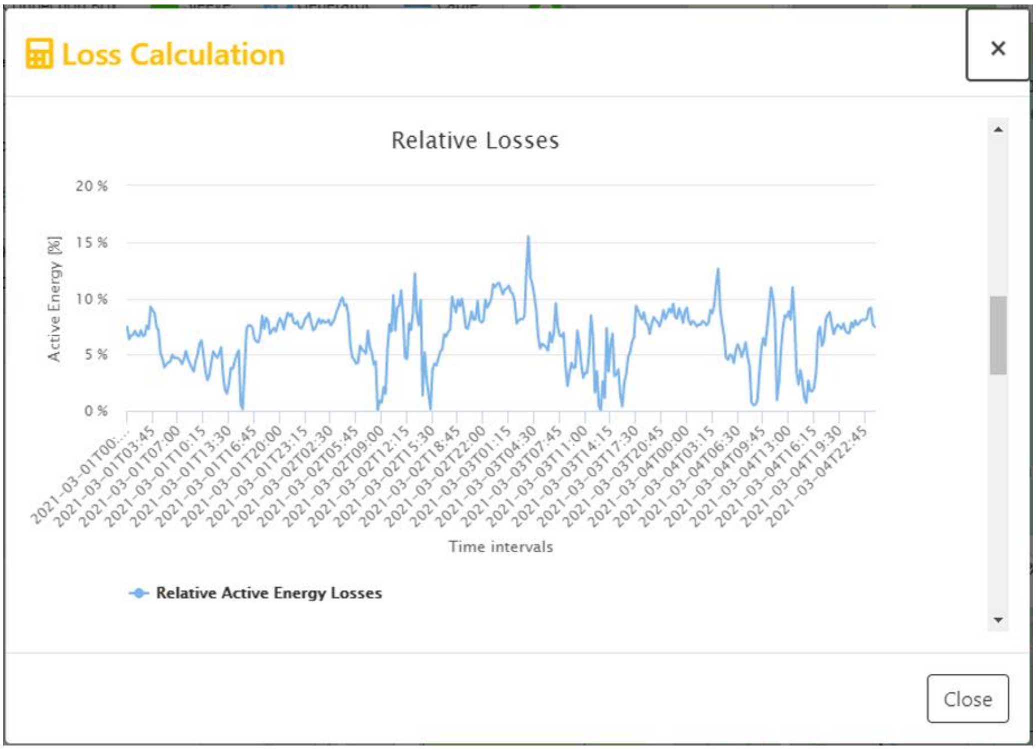

Figure 10. Relative losses at substation level in TME field trial.

The results from TME field trial showed that losses can be estimated and visualized in GUI as detailed 15min resolution time series. It is also revealing that such time series may trigger the attention of the DSO operator by showing data outside the expected behaviour of a given LV distribution grid. The main purpose of the LC application in full deployments is to be able to identify poorly performing distribution grids as the starting point for loss minimization actions. These actions can be performed e.g. via voltage management or reactive power management as shown in the previous subsections. The identification of these high losses scenarios is very relevant when monitoring the behaviour of multiple secondary substations as discussed in the next subsection.

An economical evaluation of the loss reduction benefit, achieved through the implementation of Net2DG, was performed in the CBA. Utilizing the information provided on average annual grid losses by the DSOs, combined with the average annual day-ahead prices for electricity, the monetary benefit related to reduced grid losses were calculated to 5,716 EUR/year for StwL and 54,581 EUR/year for TME. More accurate values regarding the total energy supplied in the low-voltage grid is necessary in order to increase the validity of the results. However, the findings should be considered as indicators of the potential economic benefits related to loss reduction benefit achieved through the application of the Net2DG solution.

3.2.4 Challenges for Large Scale Deployment

For calculating the losses in a grid, an adequate measurement deployment is required. The complete measurement scenario contains the substation measurement and smart meters at all customer connection boxes. In terms of losses, a distinction must be made between the total losses and technical losses calculated from the line currents. Total losses are the sum of technical and non-technical losses and those are obtained by the Net2DG LC application for the full LV grid area. Technical losses, however, can be calculated by the OGM and can be visualized in detail at the feeder level for every grid element in the topology. A heat map on substation level and after zoom in on feeder level is very useful in large distribution grids to focus directly and quickly on the analysis of areas with large technical losses.

In case when there is not a fully measured customer connection box scenario, pseudo measurements can be introduced. Pseudo measurements are derived as average values and specific models for every customer types are used. The accuracy of the pseudo measurements is decisive for the accuracy of the loss calculation. In case when junction box measurements are existent, these can be used as a source to generate more accurate pseudo measurements. Such pseudo-measurement generation has been shown in Net2DG to be highly accurate for obtaining voltages along the feeder. However, the investigation of the accuracy of the resulting grid calculations for obtaining technical losses still has to be analyzed.

In a fully rolled-out Net2DG system, the DSO operator can obtain the losses and poorly performing areas and elements are then highlighted visually. In a future advanced version of the application, different options for loss minimization should be triggered from the GUI. The system analyzes various grid scenarios and presents methods for minimizing the losses such as reactive power management, different settings for tap changer, as well as possible reconfigurations in the grid. Then, the DSO is evaluating the results from these methods and it is able to select the most suitable mitigation action. Loss minimization by topology adjustment or by voltage management thereby needs to be supported by continuous subsequent grid monitoring in order to make sure that the taken measures do not affect other grid operational parameters. This continuous systematic monitoring system is currently provided by the Net2DG.

3.3 Reduced Number of Voltage Quality Problems

A common challenge in modern distribution grids with high penetration of renewable generation, in particular roof-top solar PV systems, is the overvoltage phenomena. Typically, the full solar production is experienced during mid-day hours when actually the loading in residential grids is minimal. Thus, the voltage profiles are rising along the long LV feeders exceeding the maximum limits. The situation may become worse during days with fast moving clouds. Having small wind turbines connected at the end of the feeder as seen often in rural areas may increase the impact as wind turbines may fully produce power not only during day time but also during night when the consumption is also at its minimum levels. These over-voltages may typically damage the household appliances, while grid infrastructure is susceptible to premature ageing and more failures. Two applications were developed and tested to address this challenge. GMon application is actually providing information about the severity of voltage quality problems and their frequency of occurrence while AVR is used to mitigate them. Both applications are utilizing OGM for different purposes.

3.3.1 Use Case Description

Low voltage grids with high penetration of renewable generations and new types of loads are susceptible to voltage/power quality problems. GMon application is used to monitor and identify operational scenarios when voltage is outside the admissible limits. These situations are triggering an active coordinated control of e.g. PV inverters using the AVR application. The AVR is actually improving the voltage profile along the feeders and eliminates the overvoltage events in a low voltage grid with sufficient amount of PV installations. Alternatively, the AVR may be utilized in high load situations when the grid voltage may drop below the minimum limits.

3.3.2 Digital Assessment Studies

The digital assessment studies were focusing on verifying the AVR application assuming that the GMon is detecting the voltage violations and is automatically triggering it. A modified version of one LV feeder from TME field trial was modelled in the digital assessment framework. A simple diagram of this feeder is shown in Figure 11. Additional PV systems were added in specific nodes in order to experience voltage rise problems during full PV production.

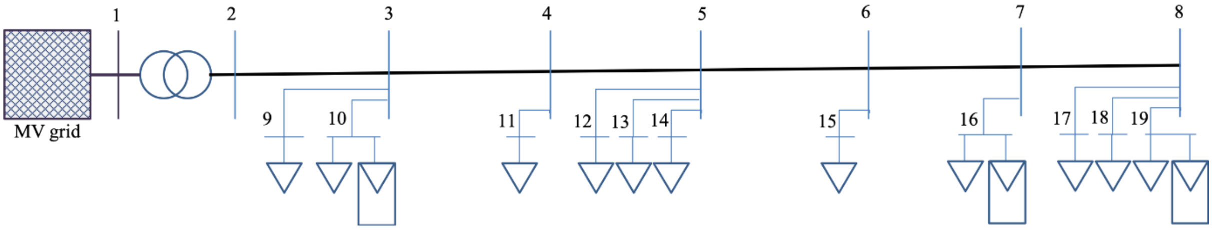

Figure 11. TME based modified feeder for coordinated voltage control using solar PV inverters

The voltage profiles during a typical summer day without using the AVR application are shown in Figure 12. It is assumed that all PV systems are operating at fixed unity power factor as recommended by Danish technical regulations. It can be observed voltage levels above the maximum limit especially at the end of the feeder.

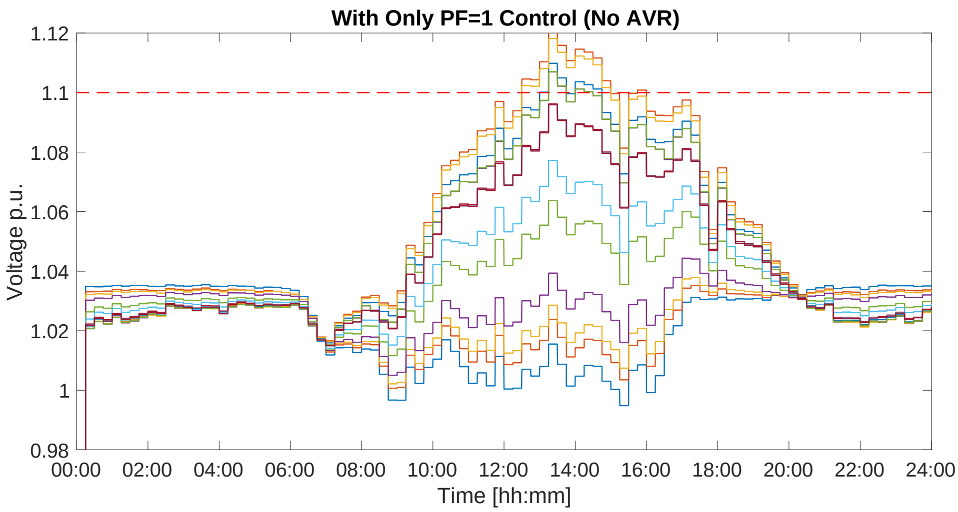

Figure 12. Voltage profiles in all customer connections without AVR support

An active coordination of PV inverters using the AVR app will reduce the maximum over-voltages while keeping all voltage profile in every node/customer connection point within the limits as shown in Figure 13.

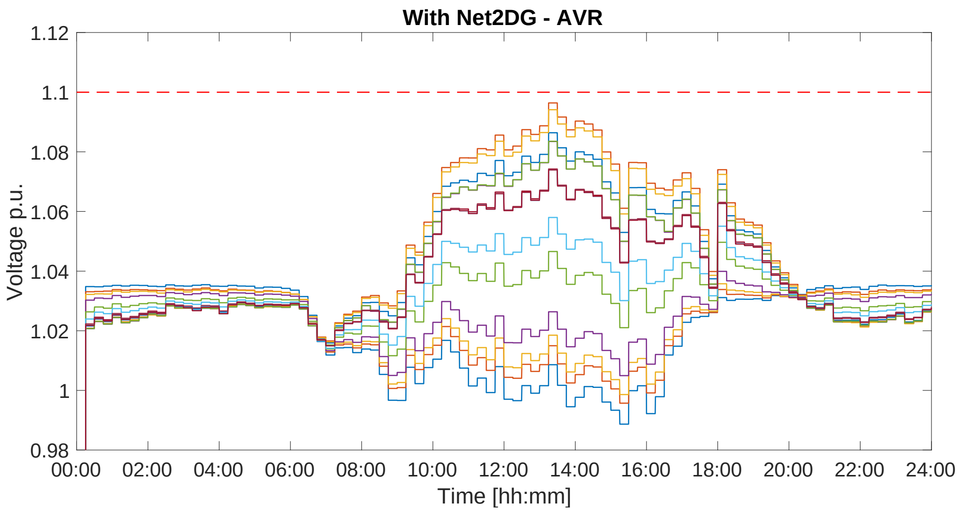

Figure 13 Voltage profiles in all customer connections with AVR support

AVR in this case is computing individual setpoints to solar PV inverters using a voltage sensitivity matrix for every node in the system provided by OGM.

3.3.3 Field Trial Results

The TME field trial was used to verify the GMon application in particular the violation of voltage limits. A set of measurements for March 2021 were exported from the AMI Head-End and analysed using GMon in a local installation of the Net2DG system. As an example of GMon results, Figure 14 shows the voltage on the secondary side of the transformer substation while Figure 15 for a selected customer connection box as presented in GUI. The DSO operator can easily see that the voltage values at both locations are fluctuating with some peaks during 14 o'clock and 18 o'clock, however, without exceeding or falling below the 10% deviation thresholds. The system also calculates and visualizes the lower and upper 10% quantiles calculated over one week time horizons, since these quantiles are important voltage quality metrics according to the European voltage quality norm EN50160. Other summary statistics and also a heatmap visualization of observed voltage quality violations are available and will enable the DSO to quickly identify and diagnose voltage problems and to support the planning processes as described later in Section 3.4.

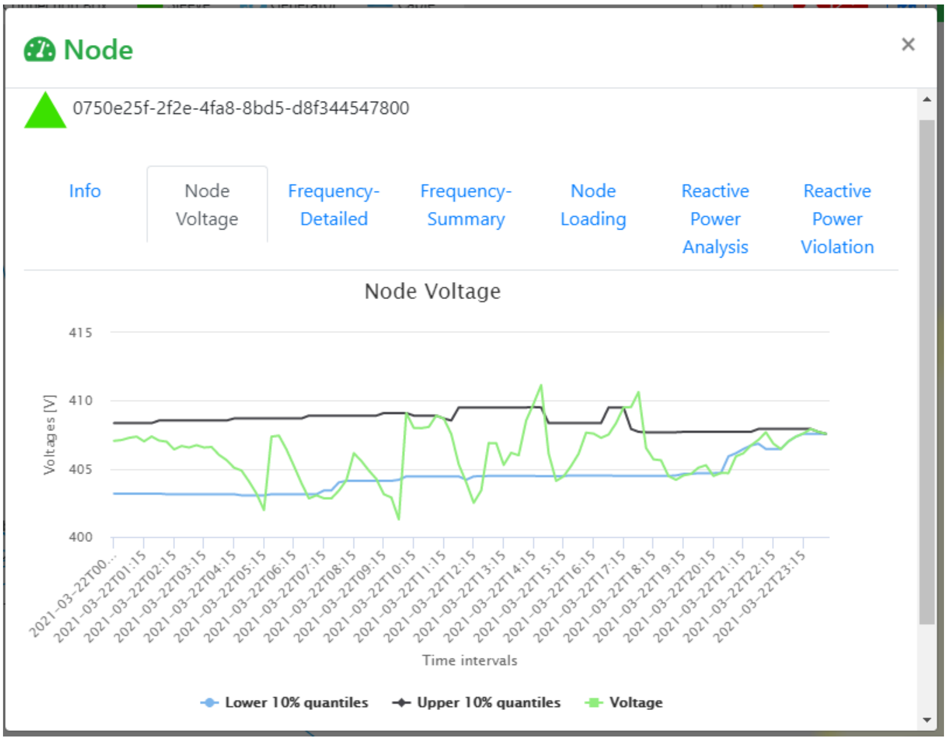

Figure 14 GMon results of substation in TME field trial.

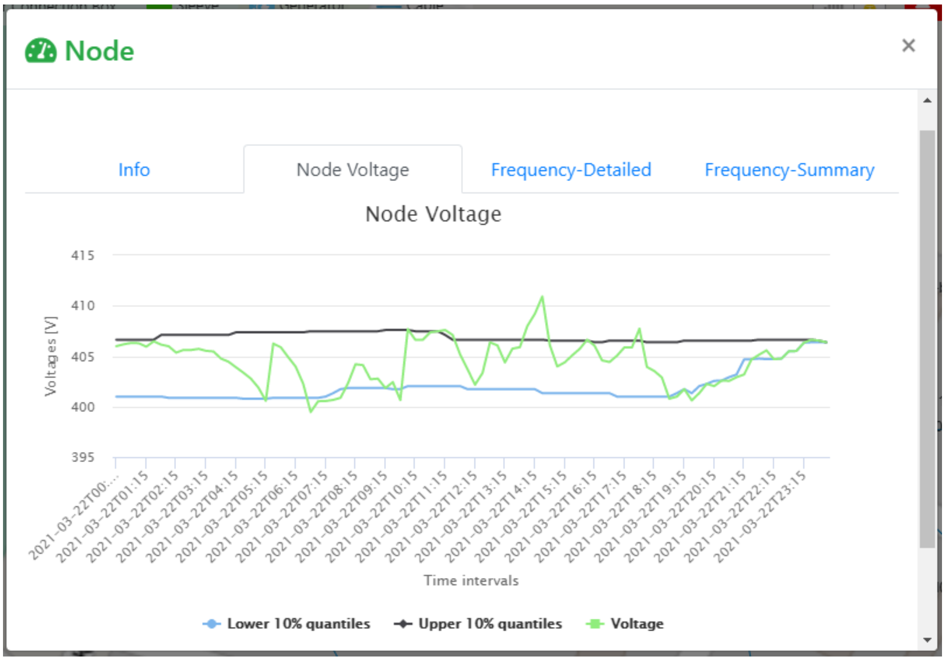

Figure 15 GMon results of a customer connection box in TME field trial.

These results are, for the selected time interval, as expected by TME, and they are also showing the potential of running GMon to continosly monitor the voltage profiles in a distribution grid. Regarding mitigation of voltage quality problems, some potential voltage violations useful for triggering the AVR were not identified. At the current time, the number of solar PV inverter installed in the TME grid was not high enough to actually demonstrate the need and effectiveness of the AVR for mittigation of voltage violations in the field trial.

3.3.4 Challenges for Large Scale Deployment

In order to reduce the number of voltage quality problems, a DSO has to firstly identify these problems by continuously monitoring the distribution grids using different data sources. GMon application is enabling the DSO operator to analyse the voltage profiles in all grid nodes for selected time periods via GUI application. These visualized voltage levels on GUI are provided by various direct measurements available from various data sources e.g. SMs, grid inverters or measurement devices placed on selected grid nodes but also estimated by OGM for those nodes where there is no data source available. Any violation of the voltage levels in any grid node can be monitored via the GUI and actually trigger the mitigation actions e.g. by enabling the AVR application. In order to support a large scale deployment where multiple secondary substations are completely monitored using GMON, a colour scheme was developed in Net2DG project to support a detailed but intuitive analysis of the areas with voltages outside the admissible limits. Thus, in case of over/under voltages, the affected area is automatically marked and the DSO operator is able to focus directly on this area without considering the unaffected nodes. In addition, an automated analysis of historical data is required in an advanced system that monitors many secondary substations. This process can be started automatically at a given time during the operational day to execute GMon on the latest available data. Thus, the DSO operator is made aware earlier of grid areas with specific voltage quality problems and not based on direct customer complaints.

When the voltage quality problems are properly identified, the AVR application can actually mitigate the voltage violations by bringing back the voltage in all nodes within the admissible limits. The deployment of AVR application requires the OGM application to compute accurately the voltage sensitivity matrix for the considered grid topology of interest. Then, it also requires an interface to the inverters to provide references for the controlled grid inverters. This interface has already been standardized and its deployment is expected to become operational during the next few years.

It is obvious that both GMon and AVR are heavily dependent on accuracy and robustness of OGM to achieve the desired results. A reliable OGM having a reduced set of measurements e.g. provided by RTUs may require advanced state estimation techniques as investigated in [12] and [13]. These approaches were investigated in Net2DG and their inclusion in the integrated system is part of future work.

Additionally, other diagnostic functions could be added to support a better decision making process for DSOs. By combining the output of GMon and LC a better understanding of voltage quality problems can be achieved as part of Grid Planning process, but also further expand the AVR to account jointly for loss minimization and voltage quality improvement making.

3.4 Reduced investment cost of DER hosting capacity

3.4.1 Use Case Description

More renewable generation such as solar PV systems is currently installed at household level. The state of the art method for identifying the grid hosting capacity is a worst-case approach. Hereby the DSO is assessing the existing infrastructure taking into account a pure infeed PV power production. The evaluation criterion is specified as the maximum infeed PV power that can be installed in a given grid without exceeding the installed capacity of substation transformer. Furthermore, the voltage increase in this worst-case scenario is estimated at the infeed points. Since no measurement data are used, the worst-case analysis provides a simplified and highly conservative approach for defining the PV hosting capacity.

Net2DG improves PV hosting capacity planning in two ways:

- Firstly, real data is used to implement a transparent and significantly more efficient grid planning method. The historical maximum transformer voltage is known as well as the actual transformer utilization. From this point of view and through continuous monitoring, it is possible, instead of the worst-case analysis, to create a real-case analysis under extreme conditions.
- Secondly, there is a limit on the installed capacity for a given low voltage feeder imposed by the upper voltage limit in low consumption/high generation cases. The solar PV systems has the technical capabilities to provide reactive power support in their grid connection point. Proper voltage coordination and control of these inverters by using the AVR app may increase the hosting capacity without grid reinforcement while keeping the voltage within the limits specified by standards.

3.4.2 Digital Assessment Studies

A modified version of one LV feeder from TME field trial was modelled in the digital assessment framework. A simple diagram of this feeder is shown in Figure 16. Initially 3 PV systems are connected as presented previously in section 3.3. Additionally maximum 4 PV systems running with unity power factor can be connected (highlighted in green) without exceeding the maximum voltage limit. The voltage profiles in all connection boxes are shown in Figure 18 a) for a limited time interval.

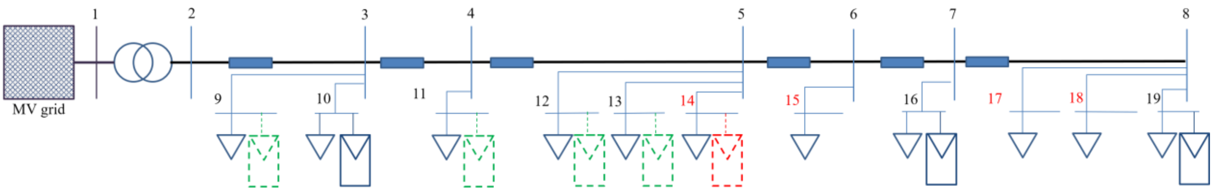

Figure 16. Maximum hosting capacity without AVR.

By using AVR, every customer from this example can install PV systems on their roof-top as shown in Figure 17. The voltage profiles in connection boxes in this case are presented in Figure 18 b). The first second of simulations are showing the actual voltage levels without AVR. Then, the AVR starts to receive data from measurements and compute references for all PV systems based on OGM results. The voltage profiles are forced to stay in the normal limits by a proper consumption of reactive power from each system.

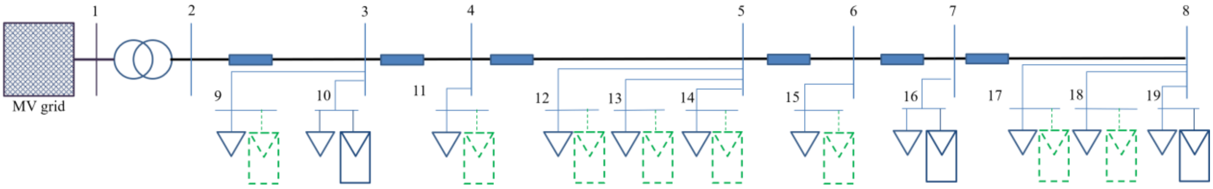

Figure 17. Increasing hosting capacity with AVR.

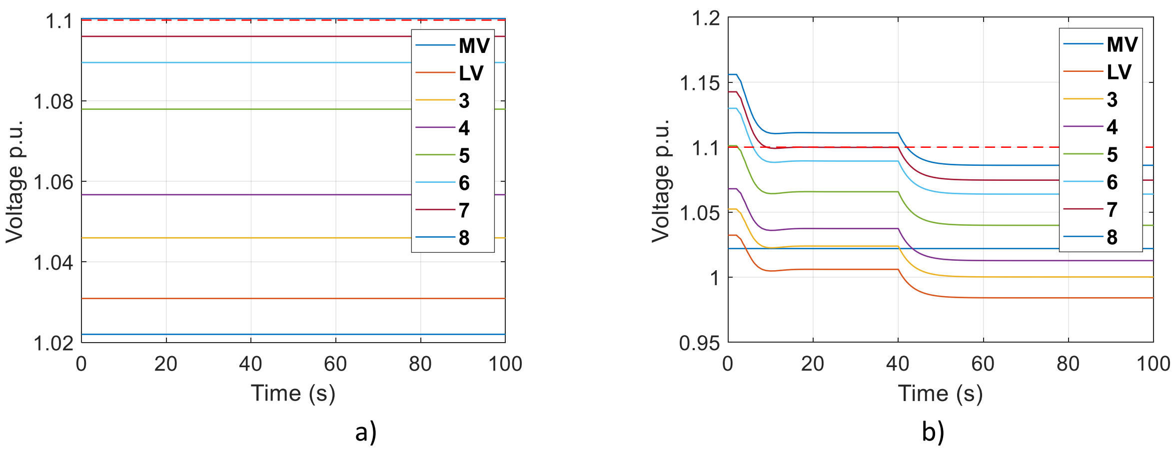

Figure 18. Voltage profiles on connection boxes: a) without AVR and b) with AVR.

Thus, in this particular setup the hosting capacity of PV systems was increased by almost 50% when AVR application is deployed.

3.4.3 Field Trial Results

During the Net2DG project, a request for a grid impact study when connecting a new PV system in StwLan field trial rose. A new PV system with the size of 19.8 kWp should be added at FI19 node as presented in Figure 19. The worst-case planning method required to exchange the transformer as the total PV capacity installed was exceeding the total transformer capacity. Furthermore, the worst case planning also showed a too high voltage increase and therefore would required a cable replacement or other topology adjustments via additional cabling. The analysis of the historical measurement data showed, however, that the transformer loading was not in a critical state during the last year of operation where a maximum loading of 70 % was identified, and that true voltages in operation were quite far from the required boundaries.

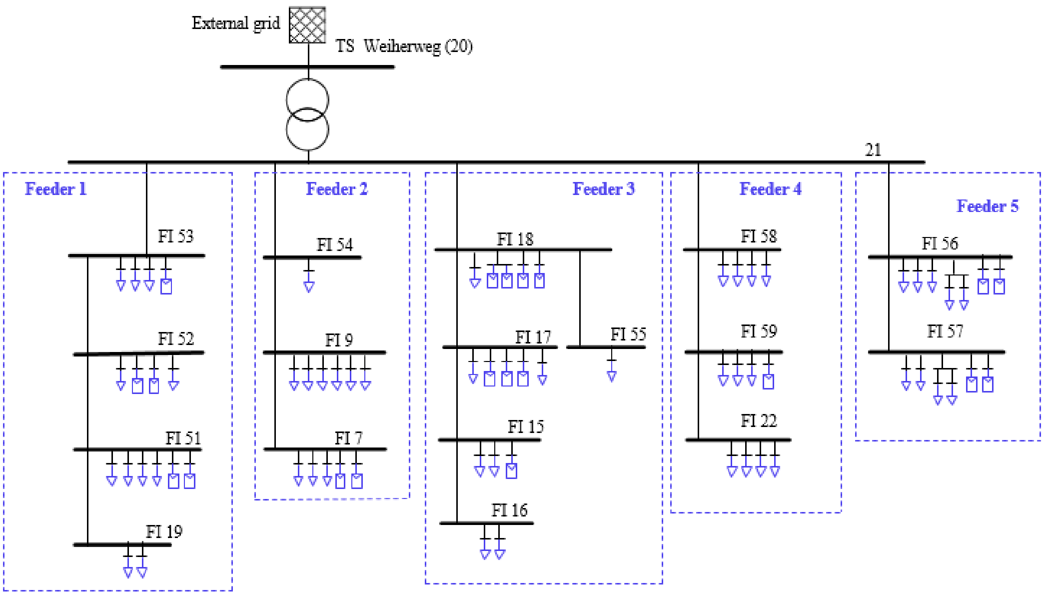

Figure 19: Grid planning scenario at StwLan

In the grid planning approach developed by Net2DG, voltage and loading data measured at the substation transformer are used in the analysis. Furthermore, a reference PV power production profile is considered to model the individual PV systems installed in Feeder 1. All other PV installations from other feeders are aggregated and considered as being directly connected at substation level by using the same reference profile This data sources and the digital twin of Feeder 1 allows to calculate the transformer loading, the cable loading and the voltages at all nodes. Additionally, in the calculation the maximum measured voltage at the secondary side of the substation transformer is considered as base voltage. By this approach, a 10 % voltage increase in the rated voltage of all nodes can used as a margin. A value of 90% is used for maximum transformer loading and cable current carrying capability.

This approach was used to assess the grid integration of a new PV system at junction box FI 19 in StwLan field trial. The results showed that there are no transformer loading challenges and the voltage will stay within admissible limits when connecting the new PV installation at node FI 19.

In order to obtain a generally applicable procedure for determining the maximum PV hosting capacity further studies were executed. Following the approach for hosting capacity evaluation introduced in Sect. 3.4.2, PV systems were incrementally connected by 3 kWp steps at all existing nodes in Feeder 1. Subsequently, the transformer loading, the cable loading and the voltage at all nodes in Feeder 1 were also assessed through the OGM of Net2DG utilizing the substation measurement and the grid topology information to retrieve realistic pseudo-measurements.

After executing the OGM-based assessment for an increasing amount of additionally connected PV, Figure 23 illustrates the transformer loading with additionally 123 kWp PV connected at Feeder 1 assessed for seven days. As shown the 90% loading limit is not exceeded by installing more PV systems in Feeder 1. Therefore, the hosting capacity until reaching the transformer loading limit is obtained in the case of additional 123kWp.

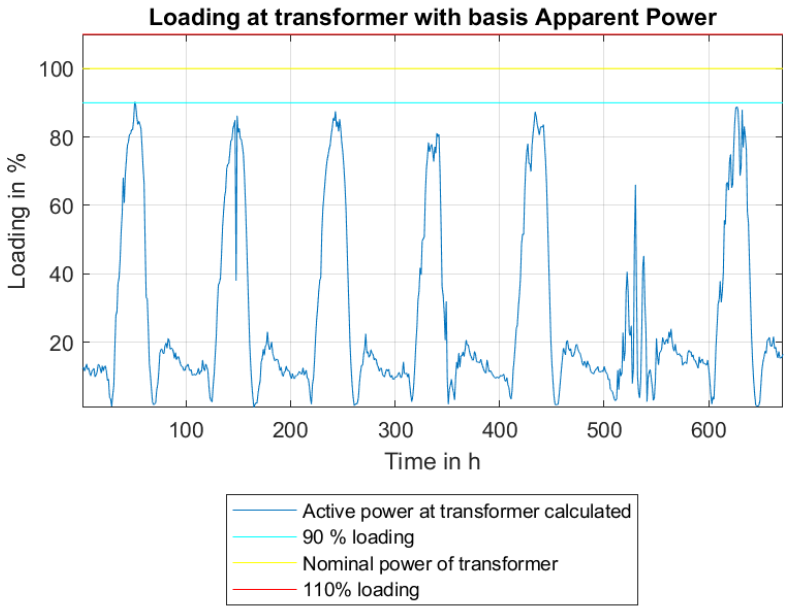

Figure 20: Transformer loading with additionally 123 kWp PV capacity distributed in Feeder 1

Another part of the digital planning approach is to consider the voltage level in all nodes as the limiting factor. Studies on the same feeder 1 were performed using the maximum measured voltage at the secondary side of the substation transformer. Thus, the voltage at all CCBs should stay within the boundary of 440V. The maximum voltage measured at the secondary transformer was 410.64 V, and using this historic actual worst case, the planning approach results in 24 kWp PV which can be connected additionally at Feeder 1, while still staying in the voltage bands at the customer connection boxes. The estimated voltages for all CCBs in Feeder 1 in this case are presented in Figure 21. The hosting capacity until reaching the voltage limits at the CCB is therefore reached with additional 24kWp.

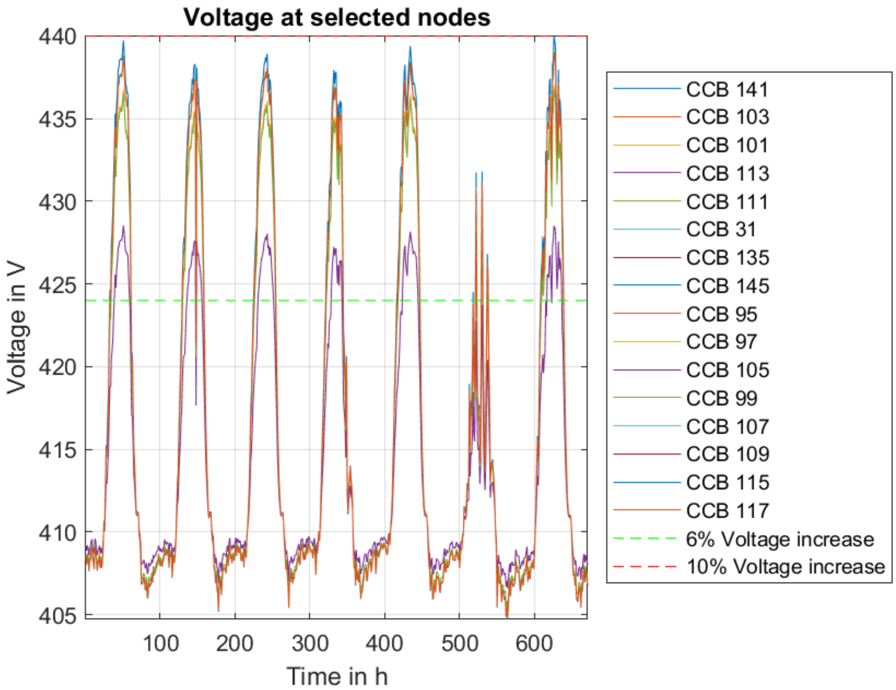

Figure 21: Voltage at nodes with additional 24 kWp PV installations distributed in Feeder 1

A summary of the resulting hosting capacity when considering different grid limitations and the improvement compared to the current planning approach for determining the PV hosting capacity for the StwLan field trial feeder is given in Table 4.

Table 4. Summary of PV hosting capacity studies

	Main Constraints	**Other constraints**	**PV hosting capacity of Feeder 1 [kWp]**	**Increase [%]**
Traditional Grid planning approach	Transformer Loading: 98% Voltage at last inverter JB: 2% of nominal	Cable loading	78 kWp	Base Case
Net2DG Approach	Voltage at CCBs 440 V (+10% of nominal)	Max trafo loading 64.9% Max cable loading 34.9%	102 kWp	**+31 %**
Net2DG Approach	Max Transformer Loading 90%	Cable loading	201 kWp	**158%**
Net2DG Approach	Max Cable Loading 90%		234 kWp	**+200%**

The results in Table 4 show that the considered StwLan field trial feeder can accommodate 31% more PV when using the Net2DG planning based on the digital twin, and then voltage limitations are reached. When utilizing approaches such as the Net2DG developed AVR application, see Section 3.4.2, the hosting capacity can be increased even further. When considering trafo loading or cable loading as the limiting factors, the hosting capacity is even much higher. Therefore, there is a substantial benefit of using the digital planning process of Net2DG that is supported by historic measurement data and should be complemented by continuous future monitoring using the GMON application and a monitoring of cable and trafo loads.

The benefit related to the increased hosting capacity enabled through the Net2DG application was monetized through evaluating the cost per kWp increased hosting capacity. The monetary benefit of the 31% increased hosting capacity results in approximately 57 kEUR cost reduction per year for StwLan and 532 kEUR cost reduction per year for TME.

3.4.4 Challenges for large scale deployment

For the calculation of the hosting capacity the OGM plays again a crucial role. The resulting CCB voltages, the loading of all cables, and the utilization of the transformer are to be taken into account when estimating the hosting capacity of a given grid. The active power, reactive power and voltage measurements over a considerable time are required for reliable assessment results e.g. one full year or at least the periods of high sun intensity in case of a grid with high PV deployment. Besides, information about the expected PV production of individual systems needs to be taking into account. One solution is to use a reference PV system based on historical PV production data. This PV reference system should be installed nearby the distribution grid under analysis and should have similar characteristics in terms of panel orientation. In large scale deployments, detailed information about consumption patterns for every customer type can be useful for an accurate assessment. However, this information may not be available in distribution grids with reduced or non-existing roll-out of smart meters. The solution applied successfully in Net2DG was to disaggregate the total power consumption measured at substation level and generate probabilistic power consumption profiles for every individual customer, as inputs to the OGM for hosting capacity studies.

4 Recommendations for Large Scale Deployment

In this chapter, the learnings and experiences from the field trials are summarized and assessed. Recommendations for a large-scale deployment of Net2DG solutions are made taking into account the needs of small and medium size DSOs. Firstly, generic challenges that are common to all functionality which requires ICT support are discussed. Then, specific challenges and recommendations for reaching a specific Net2DG target are presented.

4.1 Data Mapping and Storage

The key underlying prerequisites to ensure that all Net2DG functionalities work properly are:

1) grid topology must be captured in a digitalized format;
2) measurement data and grid topology must be correctly mapped.

The grid topology is maintained by the DSO, and each have their own internal way to document and update information about cables, junction boxes, fuses, and other elements of the electrical infrastructure. In most cases, this infrastructure is fairly old due to the long-term investment and therefore documents from previous millennium may easily be in paper format. This means that there will most likely be a manual process to convert data into digital forms, which may not be the same standardized way for all DSOs. As an example, StwLan had an Excel approach to capture this information, while TME had a company organizing data into a database from where a XML formatted CIM based data file could be extracted. Parsers were written and included in adapters at HES level for these types of files. The project demonstrated the feasibility of this approach on the two field trials where one substation was considered. Despite the small grid size, a heavy manual work to convert data was required. In this process, faults and errors may easily occur so once converted it cannot be completely trusted. Here automatic processes are absolutely required to detect such faults and inconsistencies in order to provide a high quality digital topology dataset. The amount of data for a typical medium size DSO with hundreds of secondary substations in their portfolio is too much for a manual inspection while the accuracy and correctness of topology data is critical for all Net2DG applications.

Moreover, the grid parameters used such as cable types, impedances, lengths, are also crucial in this process. Typically, these parameters are imported from manufacturers' datasheets. However, underground cables that have been installed several decades ago or overhead ones exposed to wide range of meteorological conditions, may be affected by ageing and have different parameters than the new ones. Moreover, datasheets for these old cables may have been lost or very difficult to find. DSOs may have reliable information regarding cable lengths between junction boxes in their database in most of the cases. However, this information is typically missing for the customer private cable and only approximations can be made. Thus, all these required grid parameters will also need an automatic clean up and reliable estimation techniques, which will be a continuing challenge for future work.

For the mapping process, the complexity lies in that each subsystem provider have their own way to identify measurement points. The AMI provider has serial numbers for smart meters, while the DSOs utilize an ID for each customer. These identifiers are based on internal coding schemes of a given provider and by default there is no link between them, except in the billing process. Obviously, this relation is critical for measurements to make sense when fusing large amount of data. At the same time, this also enables one to position in both space and time, information about consumers and thereby potentially becomes GDPR sensitive. First, the technical part of the mapping is not trivial as there is no strict logic that can be used to determine the relation between measurements X from a Smart Meter with grid location point Y in the grid topology data set. Future approaches by use of machine learning and artificial intelligence as well as historical data may make it possible to learn that measurement X belongs to grid topology point Y. However, in the present context, there is a critical step to realize this mapping based on existing data from and using approximate mapping with billing information. Once this relation has been created, it is easy for the system to continuously map data from subsystems to grid topology, but still there may be errors in the mapping which requires detection. Again, dedicated algorithms may be required to overcome automatically the mapping of large scale grid measurement points in a full scale deployment.

The second aspect of being able to relate e.g. consumption data with household leads to strict requirement of securing the data and the use of data as it for commercial use may become personal. The advantage of an automated digital process as investigated by Net2DG is that the use of such data is guaranteed to be limited to the set of well-defined applications with clear grid operations and planning benefit. To sum up, the following recommendation can be done:

- Topology processing requires an automatic process, as has been done in the project, and in addition validation of input data must be done automatically by the system as well. However, as long as DSOs handles their topology differently, new adapters will have to be created for new DSOs. It would be most beneficial to push for standards e.g. the CIM format for exchange of topology data. While mapping of measurements to topology may or may not require manual work to insert this into the ICT-Gateway by extractions from various databases, the mapping process will need to be done automatically at run time, as it is also done in the project. Automatic validation of the mapping should be done to ensure that data is correctly linked to the correct point of measurement in the grid.

4.2 Interoperability with AMI systems

Accessing historical load measurements of customers which are already available in the AMI system was not a major challenge, and data has successfully been collected for around eight months during the project. GMon and LC applications runs successfully using this historical data.

Applications as ODet, ODiag may on the other hand require near to real-time data such as not older than one to two minutes. In order to fully benefit the advantages of these two data access methods to critical elements must be in place for a subset of measurement devices in the LV grid area as when accessing AMI information:

1) alarms from customer meters or from the substation meter must be received and processed fast;
2) on-demand access to specific meters must be available and it must be possible to retrieve within a couple of minutes the required information for operational meters

The experiences on the TME field trial show that these two functionalities are not trivial to integrate mainly due to non-technical and security/safety constraints in the existing AMI system. In this case, the Net2DG deployment was technically separated from the actual production, by adding a redundant concentrator in the field for on-demand access. This was done in order to not interfere and perturb by accident billing oriented meter readings as required by law. Of course, this solution does not scale up. In addition, tapping into the alarm functionality becomes an interoperability challenge in the case of the IT architecture of TME as the alarms are sent to a third-party company. In a full- and long-term deployment, the AMI integration would need to be integrated with requirements from the billing system so that the two systems work without mutual influence on data collection performance.

In Germany, access to Smart Meter data is performed through the Smart Meter Gateway [9]. This gateway is standardized and thus offers the same interfaces, regardless of the Smart Meter vendor, which is an advantage compared to the Danish situation. However, the security requirements are more challenging according to German law. For instance, to access Smart Meters, one needs to be a part of a public key infrastructure, and the pseudonymisation of Smart Meter locations is making the mapping challenging. On-demand accesses and alarms are not directly supported by current commercial Smart Meter Gateways. However, feasible interfacing solutions can be found. Firstly, the Smart Meter Gateway offers a ping functionality that can replace the on-demand access. Secondly, for ODet and ODiag, an alarm support of all devices in the field is not needed. It is sufficient if alarms are provided by any meter that recognizes voltage drops caused by an outage, e.g., the substation meter as this one usually support alarms.

Since the AMI infrastructure and its performance varies between providers but also depends on regulatory framework in specific countries, a case specific evaluation regarding interoperability of Net2DG solutions is recommended. In general, applications that requires analysis of historical data e.g. GMon and LC, may run successfully in all deployments, while there are more demanding system integration challenges for near-real time applications ODet and ODiag. In summary, the following recommendations for full scale deployment should be considered:

- Alarms needs to be fully integrated which also means that the security challenges need to be completely solved for the AMI infrastructure to securely forward alarms to the ICT-Gateway. Interfaces to alarm services needs to map the alarms consistently to the internal of the ICT-Gateway, which may require additional specialized software interfaces.
- Application dependencies of on-demand readings should be limited to a minimum, since either it requires network resources that may be limited, or only support reachability functionality which may not be sufficient for all applications.

4.3 Interoperability with Inverter Systems

The design and implementation of the Inverter Adapter leveraged the SolarWeb API [16] for interfacing with the inverter HES, which provided a simple and useful approach for integration. During the initial tests some socket level issues were observed that lead to connectivity failures but have for the prototype been solved by implementing a retransmission scheme to ensure reasonable persistence. Hence, some more maturity of the interfacing code is expected to be carried out for the final deployment to ensure robustness at production level.

Future improvement to facilitate the integration and provide further features would be the usage of a new API, SolarWeb API [17], that is expected to improve the existing interface and provides several new interesting features. A feasibility study was conducted within the project timeframe. It highlighted that migrating to the new API will require some effort (e.g., different authentication, multiple metadata services, but none of them 100% corresponding to the existing ones, etc.). Therefore, it was decided to continue using the previous version of the API, while considering the new one for future development.
Access to inverter data during the project was based on individual customer agreements, which in a full deployment would require substantial effort to collect. It therefore will be beneficial, if the DSO can secure the agreement to utilize the inverter data for grid operation and planning with a well-defined set of automated applications within its connection rules and that the regulation provides the required framework to make this possible. Within the field trials in Net2DG, inverter access was constrained to Solar-Web connected inverters of Fronius. On the other hand, using the approach of extrapolating from a reference inverter, the benefits of the Net2DG planning procedure were already obtainable with one inverter within the closer geographic area providing measurement data. For applications like GMon, the desired number of connected inverters depends on the availability of other measurement data sources and therefore should be investigated on a case-by-case basis.
To sum up, the following recommendation should be considered: moving to the new API should be considered for future developments of the system.

4.4 Interoperability with RTU HES

The Net2DG field trial at StwLan used electrical measurement devices that were accessed through an RTU with cellular connectivity. When utilizing roaming SIM cards for the cellular connection and with additional measures such as external antennas, it was possible to get sufficient connection quality despite the rural area of the field test with rather poor cellular coverage. Therefore, the cellular connectivity was performance- and price-wise a viable option for connecting to substation RTUs. In case that other IP connectivity such as over fibre or copper is available to the substation, the RTUs will actually not be necessary as existing communication capabilities of the measurement device were sufficient; an approach without RTUs was chosen for a MV grid extension of the Landau field trial and showed to be feasible with low effort.
Within the project, it was an advantage to have deployed the self-developed RTUs since they gave full control of the behaviour of the field device, e.g. it was easy to include an alarming feature even if the specific measurement device in the field did not provide this alarming. The way to include such alarmingis that the RTU samples frequently (e.g. once per second) the measured voltages or power values and then generates an alarm message based on these sampled values. As this procedure takes place over a local Modbus interface, it does not create any burden for the wide area network that connects to the RTU.
When deploying electrical measurement devices and RTUs, the following recommendations are obtained:

- Using cellular connectivity is an option for the Net2DG use-cases but it may require external antennas and roaming SIM cards in case of poor cellular coverage.
- When the point of measurement is already connected via an existing IP-based communication network, the used measurement devices can be accessed without an RTU; the RTU can however provide further features, such as alarms and high-resolution measurement storage for on-demand access. In order to take a decision on the HW choice for the field deployment, the feature set of the measurement device and of the RTU should be jointly considered.
- The measurement point at the LV side of the secondary substation trafo is important for almost all Net2DG applications. Additional measurement points at selected junction boxes can be useful, but depend on the desired applications and on the availability of measurement data from other points of measurements (e.g. customer SMs, inverters).

The approach to decide these measurement points is typically done offline iteratively, i.e. run selected applications on realistic test data or on actual measurement data, add more measurement points and investigate the impact on the application outcome. This approach will use the automatically built OGM from the Net2DG system and therefore could also be automatized further in the future.

4.5 Monitoring and Estimation Applications

The OGM is a central building block for the Net2DG solution as it allows to calculate electrical parameters at all grid locations from a limited set of available measurements. Furthermore, it allows to calculate extrapolated scenarios, which are required within the digital data-supported planning process that is shown in Section 3.4.3. The special added value of the Net2DG system is that the OGM not only calculates specific static scenarios defined by the DSO, but that the model is linked to an automated combination of defined scenario data and measured network data. This means that calculations can be carried out from historical data while including other assumptions, e.g. additionally connected generation units. The OGM is also the basis for further features such as the calculation of technical losses, or the loading analysis.

The project utilized a load-flow calculation with additional measurement-based pseudo-measurements as the basis for the OGM. Assessment results show the quality of the resulting values is high for the GMon application even for partial measurement scenarios with only few measurement points per feeder. For good result quality of calculation of loadings and technical losses, generally the number of measurement points should be increased. A case-per-case assessment is needed for other grids and for other measurement scenarios, and such case-by-case analysis can in future be automated through the digital twin that the Net2DG system is building up.

For the DSO, the OGM offers added value from asset management, GIS data, and measurement data and planning tasks can be carried out effectively. This is possible without having 100 % roll-out of smart meter, and only few connected grid inverters and RTUs; therefore, the OGM strongly reduces investment needs into measurement hardware and connectivity.

Other approaches to realization of the OGM such as stochastic methods have been investigated in the project and will be assessed further for implementation in the future Net2DG solution. Also, other types of OGMs, e.g. to support ODet and ODiag in fault situations will be studied in future research.

Regarding observability applications, the modular approach of the Net2DG system allows the DSO to build up an increasing set of applications over time. Under current regulatory and market conditions, the digital process for grid planning using the digital twin and supported by continuous LV grid monitoring has shown to have the strongest financial traction, so will probably form the baseline system for most DSOs in the LV grid. Other use-cases such as loss reduction and outage time reduction are adding additional financial benefits and can be added to the system in a step wise approach.
Such an evolutionary approach to build up a fully digital set of processes is particularly interesting, since ODet and Odiag are more demanding applications. As mentioned before, both require:

1) fast forward and processing of alarms from meters (smart meters, RTUs, grid inverters or any other measurement device) through the corresponding HES in the tens of second range;
2) relatively fast on-demand access to power quality loggers of specific meters up to minute range

The Net2DG system has been assessed with a focus on LV grids. Due to the generalisation possibilities to different measurement data sources, its application is also straightforward to Medium Voltage systems. Therefore, the Net2DG solution can also be an interesting path forward to a data-driven approach for planning and operation of the MV grid. Due to the increased remote actuation possibilities in the MV grid, the coupling and the interplay to the existing SCADA systems will need to be investigated for MV deployments, in particular for control coordination applications, see next section. Summarizing the recommendation

- Use of OGM is clearly beneficial to the applications, but care must be taken in order not to exceed processing capabilities for carrying out many estimations at the same time, or similar calculations. Some caching and priority scheme should be added to assure performance when using the OGM.
- Considering more measurement points for increased accuracy, this may include decision of strategic measurement points and support for suggested points of measurements would be desirable.

4.6 Control Coordination Applications

The continuous observability of the LV grid enables new ways of adjusting the configuration of assets or components in the Low voltage grid. The approach taken in Net2DG thereby does not target central control on seconds or few minutes timescales, as such centralized approaches have shown to be not robust and cost efficient for practical deployments. Instead, Net2DG uses existing configuration options, where changes are only applied on time-scales of weeks or even much longer. Three important configuration changes were in scope of Net2DG: (1) The adjustment of existing configuration parameters of DER inverters to achieve a reactive power behaviour that increases reduces voltage violations, increases grid hosting capacity, or reduces grid losses. An automatized version of this has been prototyped and tested and shown beneficial. (2) The adjustment of tap changers at secondary transformers to achieve reduced grid losses via voltage management in conjunction with continuous voltage monitoring. This approach has been conceptually studied in offline assessment and shown to be effective. (3) The changes of grid topologies in the LV grid. The latter was only a viable option in the German field trial, but would however remain a manual process; the digital planning process of Net2DG in principle supports the data driven adjustment of the grid topology, while further studies on the achievable benefits in a wide range of grid scenarios are needed.

Focus of the Net2DG work with respect to control coordination was on the reactive power management. A standardized interface to allow the DSO to implement optimized configurations for the local controllers of the DER inverters has been defined and, through its practical deployment, the developed approach in Net2DG will become increasingly interesting. The grid observability thereby is a prerequisite to allow the derivation of optimized configurations of the local controllers for reactive power behaviour of the DER inverters. Due to the expected further significant increase of inverter-connected DERs in the Low-voltage, the relevance, and the impact of such optimized configurations for grid support will increase in the future.

5 Conclusions and Outlook

Overall, the Net2DG project initial targets i.e. (1) reduced time for outage detection; (2) reduced LV losses; reduced number of voltage quality problems and (3) reduced investment cost of DER hosting capacity were fully achieved through a set of applications, Grid Monitoring, Outage detection, Outage diagnosis, Loss Calculation and Automatic Voltage Regulations, validated in the field tests of StadtWerke Landau (Germany) and Thy-Mors Energi (Denmark) as well as in laboratory supported by multiple simulation studies. These applications rely on fused data from different measurements subsystems and data bases were successfully developed, verified and tested using a combination of field trials and a digital assessment framework. Overall, the applications were successfully working as expected, but to fully deploy these applications on top of the ICT-Gateway with its subsystem interfaces, several technical and non-technical issues still need to be resolved. Robustness of software must be ensured as well as interfaces made secure to the level of production code. As expected from a prototype some interfaces will need revisions to reach the right maturity level for a production system.

The Net2DG solutions are mainly targeting the small and medium size DSOs. Several challenges were discovered and tailored solutions were adopted to overcome them. The results obtained in the project were disseminated via several channels as part of WP6. The feedbacks received so far from the project partners that are the users of the solution, i.e. TME and StwLan, and through national workshops with demonstration of the applications are positive and confirm that part of the solutions developed and proposed in the project are close to market commercialization (consideration of TRL=8).

The numerical analysis of the results obtained through the combination of field trial analysis, laboratory setup, and offline analysis showed the following benefits: (1) Outage detection and diagnosis time could be reduced to few minutes (2) grid losses could be reduced by 11% via voltage management applied in combination with continuous voltage monitoring; when applying a variant of the reactive power coordination of inverters, even a reduction by 20% was possible. (3) The hosting capacity of the field trial example grid was increased by 30% through an enhanced planning process using the digital grid status, and an additional 50% increase was achievable through the coordinated reactive power management of the inverters. Therefore, the results clearly show the benefits of the developed Net2DG solution for the future digital operation and planning of the low-voltage grids and that such digitalization will be a critical contributor to the realization of the energy transition.

References

[1] K. Handrup (edt.), “Net2DG Deliverable D1.2 – Initial Baseline Architecture”, August 2019;

[2] N. Nostro (edt.), “Net2DG Deliverable D3.1 - ICT Analysis and Gateway Design”, December, 2018

[3] N. Nostro (edt.), “Net2DG Deliverable D3.3 - ICT resilience mechanisms and verification”, June 2020

[4] J. Bendtsen (edt.), “Net2DG Deliverable D4.1 - Actuation Schemes and Control Coordination Approaches”, December 2019

[5] J. Bendtsen (edt.), “Net2DG Deliverable D4.2 - Actuation and Coordination Prototype”, December 2020

[6] F. Iov (edt.), “Net2DG Deliverable D5.1 - First integrated deployment at Lab and Testbed and preliminary results”, December 2019

[7] K. Shahid, E. Schiavone, D. Drenjanac, R. P. Bæklund, R. L. Olsen and H. Schwefel, "Extraction of CIM-Based Distribution Grid Topology Information for Observability," 2019 15th European Dependable Computing Conference (EDCC), Naples, Italy, 2019, pp. 165-170. doi: 10.1109/EDCC.2019.00040

[8] K. Shahid, E. Schiavone, D. Drenjanac, M. Lyhne, R. L. Olsen and H. Schwefel, "Handling Incomplete and Erroneous Grid Topology Information for Low Voltage Grid Observability," 2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), Beijing, China, 2019, pp. 1-6. doi: 10.1109/SmartGridComm.2019.8909747

[9] Bundesamt für Sicherheit in der Informationstechnik (BSI), “Technische Richtlinie BSI TR-03109-1 Anforderungen an die Interoperabilität der Kommunikationseinheit eines intelligenten Messsystems”, 2019.

[10] C.-I. Ciontea, K. Shahid, F. Iov, R. L. Olsen, Flexible Platform for the Study and Testing of Smart Energy Systems Enabling-Technologies, Proceedings of the 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 2020

[11] M. S. Kemal, L. Petersen, F. Iov, R. L. Olsen, A Real-Time Open Access Platform Towards Proof of Concept for Smart Grid Applications, Journal of Communication, Navigation, Sensing and Services, ISSN: 2246-2139, Vol 1., p. 49-76, Feb 2018

[12] Nainar, K. & Iov, F.Smart Meter Measurement-Based State Estimation for Monitoring of Low-Voltage Distribution Grids, I: Energies. 13, 20, 5367, October 2020;

[13] Nainar, K. & Iov, F., Three-Phase State Estimation for Distribution-Grid Analytics, I: Clean Technologies. 3, 2, May 2021

[14] Voltage characteristics of electricity supplied by public electricity networks, 2010, EN 50160:2010.

[15] CEN-CENELEC-ETSI Smart Grid Coordination Group, Smart Grid Reference Architecture, November 2012

[16] https://api.solarweb.com/thirdparty/swagger/ui/index

[17] https://api.solarweb.com/swqapi/index.html#/