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**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This deliverable contains original unpublished work except where clearly indicated otherwise.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.

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## List of Acronyms

| | |
|---|---|
| Net2DG | Leveraging Networked Data for the Digital electricity Grid |
| AMI | Advanced Metering Systems |
| API | Application Programming Interface |
| DB | Data Base |
| DSO | Distribution System Operator |
| EM | Electrical Measurement |
| GMon | Grid Monitoring (application) |
| GUI | Graphical User Interface |
| HE | Headend |
| ICT | Information and Communications Technology |
| ICT GW | ICT Gateway |
| LC | Loss Calculation (application) |
| ODet | Outage Detection (application) |
| ODiag | Outage Diagnosis (application) |
| OGM | Observability Grid Model |
| OLTC | On-load tap changer |
| PM | Preventive Maintenance (application) |
| PoM | Point of Measurement |
| VMS | Virtual Measurement Sub-system |
| RTU | Remote Terminal Unit |
| TSO | Transmission System Operator |

# 1 Executive Summary

This deliverable captures the current status of the architecture of the Net2DG solution. This deliverable builds on the achievements and results obtained in Deliverable D1.1 and Deliverable D1.2:

- D1.1 'Case Study Specifications & Application Requirements' [1] - presents the use-cases for Net2DG and derives requirements from these use-cases on Net2DG applications and on the Net2DG ICT Gateway.
- D1.2 'Initial Baseline Architecture' [2] - introduces the overall system architecture of the Net2DG solution and its system context for execution. Deliverable D1.2 served as the basis for application development and for the ICT Gateway and interface development in the Net2DG project.

This deliverable contains an update to the initial architecture that was documented in Deliverable D1.2
Chapter 3 describes the final Net2DG architecture with a focus on the ICT Gateway. One of the main targets of the project is to provide a set of observability and control coordination applications. The applications that are under development and their impact on the architecture are summarised in Chapter 4 of this deliverable. In addition, the Net2DG solution uses grid models in different places; these grid models and their placement in the Net2DG architecture are also explained in Chapter 4. Network communication is a crucial part of the Net2DG solution and this is described in Chapter 5. Three different deployments of the Net2DG solution are in operation as part of the Net2DG project: (1) a Real-Time Hardware in the Loop Laboratory, (2) the field-trial site of Thy-Mors Energi, (3) the field-trial site of Stadtwerke Landau. The architecture of these three setups are different from each other, and are all described in Chapter 6.

# 2 Introduction and Use-Cases

Purpose of Deliverable D1.3 is to present and summarise the achieved results that have implications on the final base-line architecture of Net2DG. The base-line architecture was derived from the original proposal presented in D1.2 [2] according to the progress of the detailed design, implementation, and integration in the Net2DG project. A summary of targeted user stories and their prioritization are presented in the following paragraphs.

## *2.1 Use-cases*

This chapter contains an overview of the use-cases and stories. These are fully described in Deliverable D1.1 [1]. Deliverable D1.2 [2] shows detailed message sequence for how these use-cases operates within the architecture. The use-cases in question are: grid outage detection and diagnosis, preventive maintenance of low voltage grid assets, detection and localization of neutral fault, reactive power and voltage quality monitoring and control, loss calculation, minimise losses in the low-voltage grid, minimize energy exchange with TSO. These use-cases are described in detail in deliverable D1.1 [1].

In addition to these use-cases of direct benefit for the DSO, the Net2DG system also required system administration and master data management. These use-cases are described in Deliverable D1.2 [2].

## *2.2 Prioritisation of the use-cases*

The use-cases have been prioritized as shown in Chapter 7 of Deliverable D1.1 [1] based on feedback from all consortium partners and from the additional DSOs in the reference group.

The prioritisation of the use-cases are the following:

1) Outage detection (ODet)
2) Loss calculation and recording (LC)
3) Preventive maintenance (PM)
4) Outage diagnosis (ODiag)
5) Low-voltage grid monitoring (GMon)
6) Neutral fault diagnostic and location
7) Automatic voltage regulation
8) Calculate and visualize energy/power exchange in interconnection points to TS and overall in DS grid
9) Neutral fault detection
10) Loss minimisation by grid reconfiguration
11) Recommend improvements to the DS grid to minimise energy exchange from TS grid
12) Loss minimisation using interaction with flexible energy resources.

This prioritisation is described in greater detail in Deliverable D1.1 [1]. The first five use-cases have been selected for design and implementation as observability applications in Net2DG [3]. In addition, the use-case 'Automatic Voltage Regulation' has been selected for design and implementation as control coordination application in Net2DG. See Deliverable D1.1 [1] for more information.

# 3 Final System Architecture

The high-level system architecture of the Net2DG solution is shown in Figure 1. The Application Layer includes the targeted application as introduced in Chapter 4. The applications retrieve the grid topology information and the measurements from the ICT Gateway, which establishes connections to the different data and actuation subsystems: The final selection of measurement and actuation subsystems that are used in addition to the Grid Topology Subsystem are:

- AMI subsystem
- Inverter subsystem
- EM subsystem (using Janitza measurement devices in Net2DG)

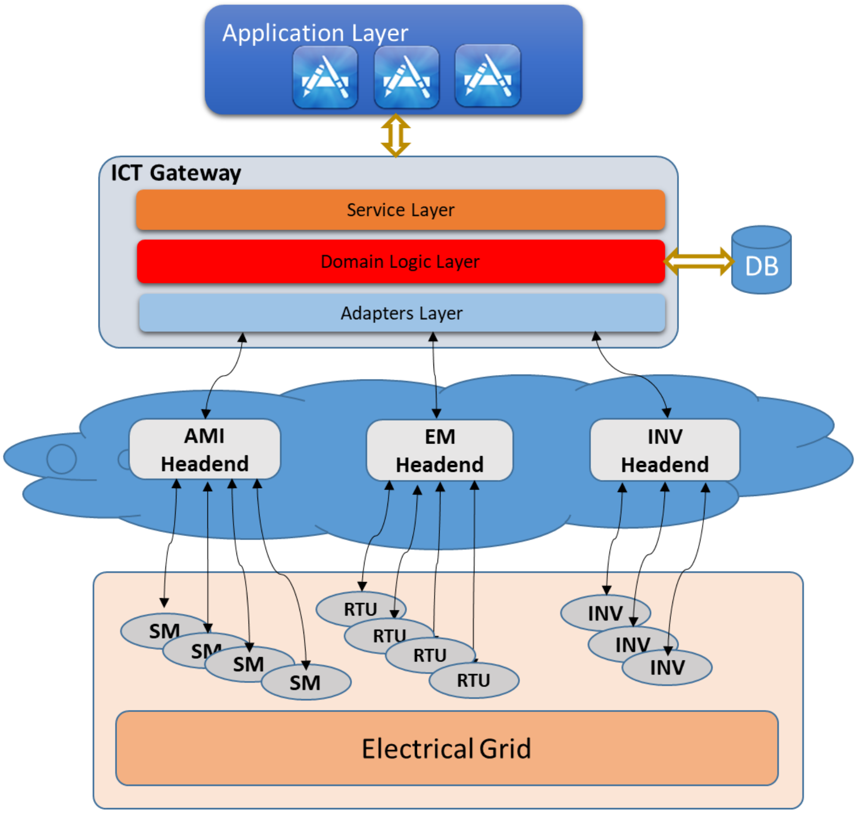


**Figure 1: Final Architecture of the Net2DG system**

The development of the detailed system architecture has taken its starting point from the system requirements that were initially defined in Chapter 4 of Deliverable D1.1 [1]. This section first reflects on the status of these system requirements. The central element in this system architecture is the ICT Gateway (ICT GW), for which the final architecture is shown in the last part of this section.

## *3.1 Update on System Requirements*

The system requirements have been originally derived in Chapter 4 of Deliverable D1.1 [1] and remained unchanged since then. This following table comments on the status of these system requirements.

| | |
|---|---|
| Requirement | **Scalability:**<br>SYS-01: The Net2DG solution must be able to support the processing of grids with up to 50.000 measurement points and up to 2000 secondary substations.<br>SYS-02: The actual prototype deployment in Net2DG must support the handling of grids with up to 5000 measurement points and 200 secondary substations. |
| Net2DG status | Since the ICT GW is still in a prototype phase, the focus during the whole project will be on the requirement SYS-02. The main component to support this requirement is the ICT Gateway. So far the focus was on functional tests during which the ICT GW operated with 2-3 substations and around 400 measurement points. No performance problems emerged during those tests. A more detailed scalability analysis is planned during the last 12 months of the project. |
| | |
| Requirement | **Availability:**<br>SYS-03: The Net2DG control coordination should work in such a way that unavailability of the Net2DG system does not create safety-critical grid behavior or large scale blackouts.<br>SYS-04: The Net2DG solution should have a maximum downtime of 100 hours per year (98,85%). |
| Net2DG status | Net2DG control functionalities pertain to adjusting the power generation of Fronius inverter. The control system is designed in such a way that its unavailability does not introduce any safety-critical behaviour. The integration of such functionality is planned during Year 3.<br>A conceptual availability analysis based on field test experience is planned during the last 12 months of the project. |
| | |
| Requirement | **Security:**<br>SYS-05: Authenticity, Integrity, and confidentiality: Requirements for ensuring authenticity, confidentiality and protecting messages integrity shall be identified, and appropriate controls identified and implemented. |
| Net2DG status | The ICT GW mainly receives data from head-end servers that are partially deployed at DSO premises and as such only work with data inside the DSO’s local network. In some other cases, such as access to the Fronius SolarWeb server, data protection is already implemented on the server side. Only in the case of the Electrical Measurements (Janitza), Net2DG implements the complete data workflow, i.e., from the field device to the ICT GW at the DSO. In that case, secured Web Socket connection between RTU and Headend server, and from there to the ICT GW provides for authentication and data integrity.<br><br>ICT GW requires authentication on the following interfaces:<br>- headend systems have to authenticate with adapters |

| | |
|---|---|
| | - applications have to authenticate with Application API<br>- users will need to authenticate themselves through UI |
| | |
| Requirement | **System platform:**<br>SYS-06: The Net2DG solution must be able to run on a standard Microsoft Windows platform (both virtualized and physical). Support for server 2016 is mandatory, while server 2012 R2 is optional.<br>SYS-07: For small installations and test purposes, it must be possible to execute on a single server instance.<br>SYS-08: For larger installations, it must be possible to install individual parts on separate servers. Support for multiple instances of high-load services for load balancing purposes is optional. |
| Net2DG status | The ICT GW has been running on different local machines, due to the distributed development team, all running on Microsoft Windows 10. Because the whole Net2DG software solution is based on Java, abstraction level by means of Java Virtual Machine is present on any type of operating system. Consequently, migration to a cloud-based solution is seamless.<br><br>During the development phase, ICT GW was always running on a single instance.<br><br>The Database, as a separate component of ICT GW, can be running on a separate server instance. The same applies for subsystems, with headend servers as the point of contact for the ICT GW. |
| | |
| Requirement | **System maintenance:**<br>SYS-09: It must be possible to install and upgrade the Net2DG solution.<br>SYS-10: It must be possible to install Software updates and addition of new adapters in the Net2DG prototype locally by direct physical access to the executing machines as well as remotely.<br>SYS-11: Software maintenance should only be possible with the right credentials. |
| Net2DG status | In the prototype phase it is possible to install and update the system either by direct local presence or using a software for remote access, e.g., TeamViewer.<br><br>In order to perform either an installation or update, a user first has to be logged in host operating system, e.g., Windows 10, and also have an admin role. However, this is to be configured on the operating system level. |
| | |
| Requirement | **System troubleshooting:**<br>SYS-12: All Net2DG components must support debug logging; As default, log level should be “warning”. Log files should be stored locally. |

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| | SYS-13: It shall be possible to activate a detailed tracing of actions by a local configuration.<br>SYS-14: Log files for debug purposes must not contain privacy sensitive information.<br>SYS-15: The system must make a separate audit trail for any action done by the operator. |
| Net2DG status | Net2DG components support different levels of logging and they are configured to log in the console as well as to file system.<br><br>Net2DG system does not contain any privacy-sensitive data, however in some cases it can have home addresses but it does not store them in log files.<br><br>ICT GW still has to be extended in a way that it refines logging of user actions. At the moment these are logged together with other data and thus can be cumbersome to distinguish them. |
| | |
| Requirement | **System clean-up:**<br>SYS-16: The Net2DG solution must assure that stored data is persistently removed after a configurable time period. |
| Net2DG context | Retention time has to be configurable parameter that each DSO can set separately. At the moment this feature is not yet implemented as the focus so far was to get the basic functionality in place so that the first set of applications can be tested on top. |

**Table 1: Status of system requirements**

## 3.2 Final ICT Gateway architecture

This section describes the final architecture of the ICT Gateway (ICT GW), its components and the main functionalities that it has to provide both internally and to the other components of the overall Net2DG system.

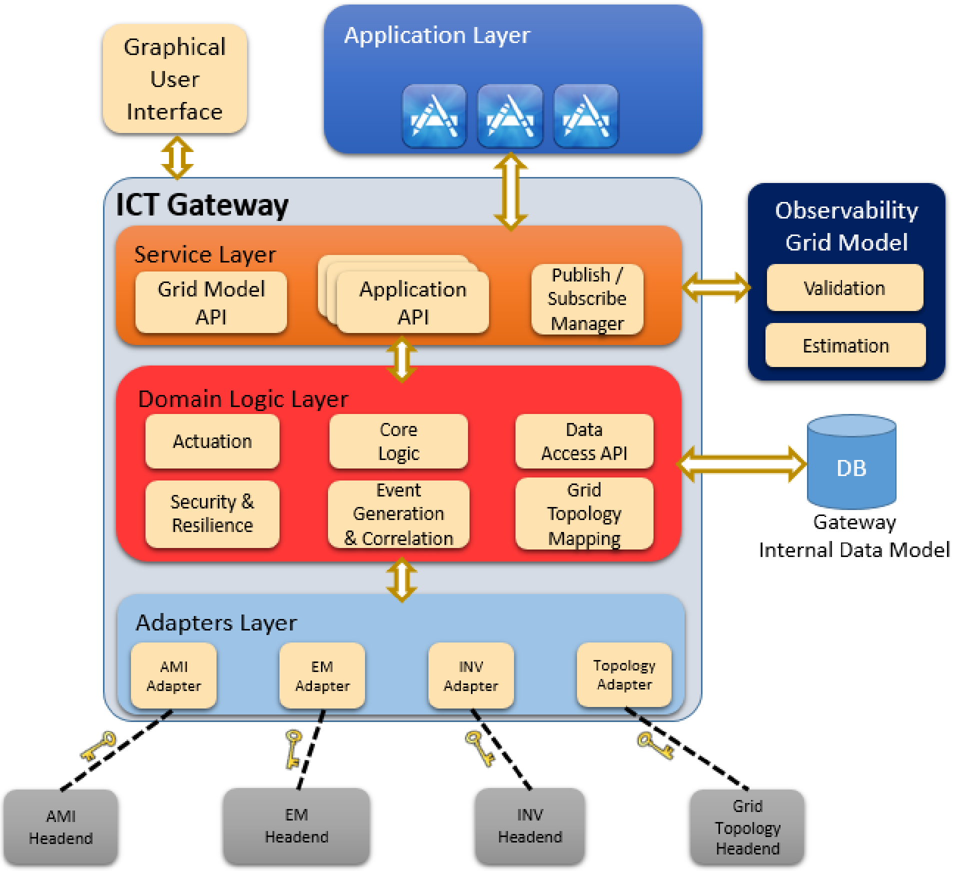


**Figure 2: Final ICT Gateway architecture, adapted from D3.1 [4]**

The main functionalities are captured inside different modules that are shown in Figure 2. The main building blocks of the ICT Gateway are divided into different layers:

- Service Layer in ICT Gateway
- Domain Logic Layer in ICT Gateway
- Adapters Layer in ICT Gateway

***Service Layer*** in ICT Gateway includes the following modules:

- Grid Model API: The Grid Model API triggers validation and estimation from the Observability Grid Model (described in Chapter 4).
- Application API: Allows interaction between ICT GW and all the Applications (described in Chapter 4) by mean of specific methods called by each of the applications
- Publish / Subscribe Manager: Supports publish/subscribe and request/reply communication paradigms and allows applications to subscribe on particular information, i.e., specific data types or events

***Domain Logic layer*** in ICT Gateway includes the following modules:

- Actuation: Handles interactions with actuation subsystems (through Headend), e.g., Inverter-systems, Load Activation, Generation curtailment, and OLTC.
- Security & Resilience: Fault and Attack detection mechanisms, functions and controls implemented to provide security, resilience and robustness (e.g., failing devices or lack of communication), see [11] for an overview and [6] for a specific example approach.
- Core Logic: contains core business functions of the ICT Gateway, which acts as mediator between data sourcing, actuation subsystems and domain applications.
- Event Generation and Correlation: Generates events correlating multiple measurements collected from different devices deployed on the field.
- Data Access API: Provides access to the Data base in order to **Create, Read, Update and Delete**, for each entity relevant information according to the Gateway Internal Data Model (e.g., topology, measurements, events, metadata).
- Grid Topology Mapping: Identifies the generator of an event/data and associates it with node id defined in the Grid Topology. It furthermore enriches data with metadata available from the Grid Topology.

***Adapters Layer*** includes the following modules, which allow interaction with field subsystems, namely the Headend:

- AMI Adapter: Connects the ICT Gateway to AMI Headend System to get data from Smart Meter infrastructure
- EM Adapter: Connects the ICT Gateway to the EM-HE, which in Net2DG will be specifically used to connect to RTUs which obtain data from Janitza devices. The EM Adapter will obtain both measurements and alarms.
- Inv. Adapter (SolarWeb Adapter): Connects the ICT Gateway to the Inverter SolarWeb Headend to get the data from PV System
- Topology Adapter: Connects the ICT Gateway to the Grid Topology Headend [8, 13] in order to get information about the topology (e.g., number of nodes, number of cables) and to receive any kind of modification of the topology.

Besides the layers described so far and related modules, other elements constituting the ICT Gateway Architecture as shown in Figure 2 are described in the following.

- GUI: Provides input and output (mostly visualisation) for both Applications and for ICT Gateway functionalities of the Net2DG system and that way enables the interaction with the human operator on site.
- Data Base (DB) Stores the data models: measurements, events and grid topology. The data can be equipped with metadata, as well as subscriptions information.

Main interfaces involving ICT GW are related to Applications, the Observability Grid Model (OGM) and Headend systems as shown in Figure 2. Interaction between an application and Application API of the ICT GW is realized by means of REST and Web Socket. Interaction with the OGM is based on WebSocket where ICT GW acts as client and OGM as Server.

Adapters and Headend interact by means of exchanges of messages that are formatted as JSON objects and are exchanged either over established WebSocket connection or through HTTP Request/Response messages.

Finally, interaction with the Data Base is based on messages (i.e., Java object) that allow to Create, Read, Update and Delete data on the Data Base.

# 4 Applications and Grid Models

The applications that implement the selected high-priority use-cases are described in this Chapter. The Net2DG project uses an iterative approach: the so-called Release 1 version contains a basic set of features and works with limited data (for instance, some Release 1 applications only use lumped values instead of per-phase values for electrical variables in the grid). The architecture evolution is mainly shaped by the design and implementation of these Release 1 application. The project will however evolve the applications further in subsequent implementation iterations (Release 2 and beyond). As the applications are enabled and tested by grid models [15], this chapter first gives an overview on the grid models in Net2DG.

## 4.1 Grid Models

Grid models are used for two different purposes in Net2DG. The first one, called Reference Grid Model (RGM), is used for assessment of the Net2DG applications; the second one, called Observability Grid Model (OGM), is used to calculate electrical parameters for the grid observability applications (e.g., calculate voltage values for all grid nodes in the LV topology). These two types of models are visualized in Figure 3 and are summarized in the following based on D2.1 [3] for further details.

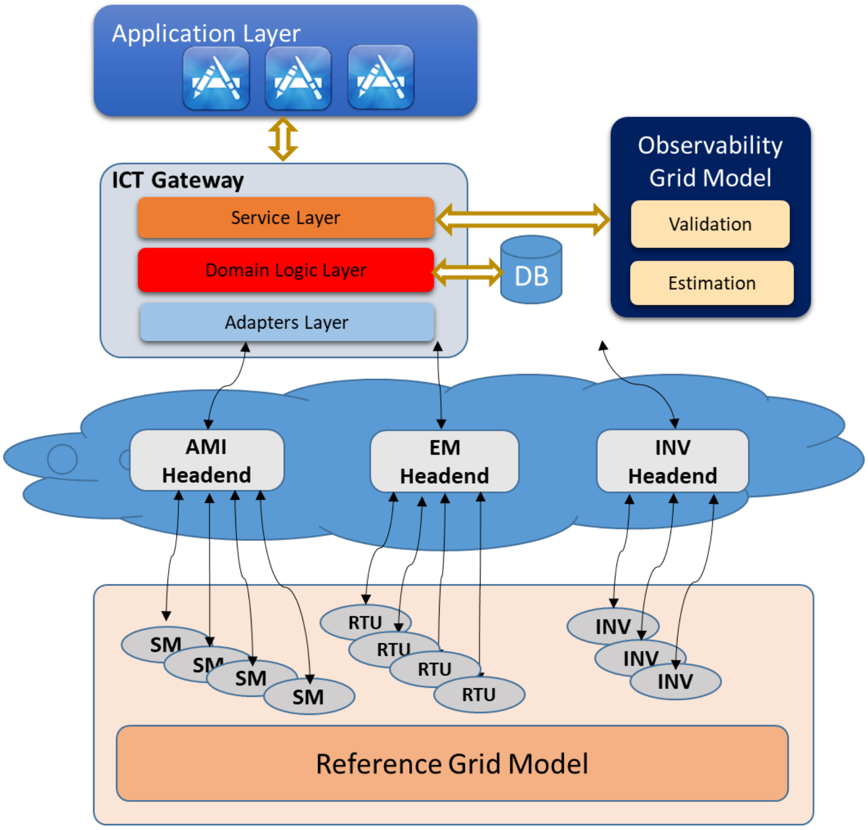


**Figure 3: Reference Grid Model versus Observability Grid Model based on D2.1 [3].**

The Net2DG project has developed different variants of grid models, which can be used as RGM or as OGM. These variants are justified by the following requirements:

- Initial development and testing of applications requires simple but still accurate simulation tools available for any developer to represent the low voltage grids. Dedicated simulation tools as reviewed in D2.1 [3] are bound to expensive licenses while some of the open ones are not having proper support. These dedicated tools may also require co-simulation for various part of the entire Net2DG system under consideration thus increasing the complexity in the verification stage.
- DSOs may have access to a limited set of measurements from available measurement devices. A standard setup in AMI is providing only lumped values for active and reactive power measurements for all three phases. Hence complex models are not necessary in this case.
- Specific applications i.e. detection of neutral faults are requiring complex models which typically are available only in dedicated simulation tools. By benchmarking various models, limitations and guidelines for utilization of the simple ones can be drawn.
- Computational requirements for complex models may increase substantially the cost for the host platform. Thus, tailored solutions in terms of cost are considered for small and medium DSOs.

The model variants developed and verified are as:

- 1-wire model: This is the simplest and fastest model as it only uses a positive sequence representation of the power system. The model calculates a load flow based on an iterative backward-forward calculation. It is used for balance and symmetrical loading combined with the measurement of average active and reactive power for all three phases provided in standard setups for e.g AMI.
- 3-wire model: In order to study unbalanced scenarios it is necessary to use a 3-wire modelling, which distinguishes phases a-b-c. In this model, different loads and generations can be defined per phase, being the result closer to reality. This approach has approximately three times more computational needs than the 1-wire, however its result are comparably better than the 1-wire. This approach is also requiring measurements per phase.
- 4-wire model: It is important to account for the neutral but also for the grounding system in distribution grids in order to predict the behaviour during high unbalances and asymmetrical faults. If the whole system is modelled with the 4–wire approach a better estimation of the grid's state can be achieved. Obviously, this is the most complex of the three approaches, but also is the most accurate one. On the other hand, the 4-wire modelling approach for very large power systems is very challenging in terms of computational burden.

The 4-wire model is developed as a benchmark to evaluate the fidelity and accuracy of the 1-wire and the 3-wire respectively. This benchmarking is using a relevant detailed configuration of a representative low voltage feeder. Scaling up the grid representation to a substation or multiple substation level will not compromise the accuracy of the results. The project is considering the 3-wire model for testing and verification of the applications.

All implemented models provide as output at least voltage phase-to-neutral in all grid nodes and currents in all grid lines. In addition to the grid topology including cable parameters, the above models require as input to active and reactive power values at all loads and generators and the reference voltage in the grid i.e. secondary substation. This input is available when used as RGM but also as OGM. The available input depends on the measurement device deployment scenario and on the availability of the measurement data. As such further scenarios are interesting as described in the following.

## *4.2 Dealing with incomplete data*

Using the above grid models has some limitations in scenarios with incomplete measurement data, because the grid estimation techniques require to have measurement of active and reactive power at every consumer and generator node in order to be computed. However, this might not be the case if, for not all customers are measured, or measurements are lost during transmission, or the delay is unacceptably high.

Net2DG has designed and implemented solutions for the latter scenarios with two different approaches summarized in the following:

1. Obtaining Pseudo-measurements: When grid estimation is using OGM and there are customer nodes without measurements available, pseudo-measurements are generated based on historic data or based on values of 'similar' customers. Different approaches for generation of pseudo-measurement are currently investigated and compared in Net2DG. Details on these methods will be presented in upcoming publications and deliverables.
2. Grid calculations using stochastic estimation: Net2DG has developed a grid calculation model documented in [12] that works with input measurements of voltages and currents at any subset of grid nodes. In addition to the measured electrical variables, also the standard deviation of the measurements must be provided as input to the model; the latter can be obtained from specifications of measurement device errors and also clock inaccuracies can be mapped to measurement errors [5, 9]. The method then calculates expected values and standard deviations of all voltages and currents in the grid, which subsequently can be used to derive confidence intervals for all electrical values, see [12]. The approach nevertheless requires a sufficiently large number of input measurements. In order to reach that condition, pseudo-measurements of voltages and currents can again be used. Different to Approach 1 above, the uncertainty in the pseudo-measurements can now be represented by a high standard deviation of the pseudo-measurements, which also allows to use less sophisticated pseudo-measurement generation (e.g. by a constant value with large standard deviation, e.g. V=230V+-20V). Net2DG [12] has applied this approach successfully to first test scenarios with missing measurements at customer sites.

## *4.3 Overview of the observability applications*

Five use-cases have been selected by prioritization for implementation in Net2DG, and these use-cases are implemented by one application each. These five observability applications are summarized in the following table:

| **Use case ID** | **Name of the application** | **Priority** |
|---|---|---|
| UC FM-1: **Outage Detection** | ODet | 1 |
| UC LM-1: **Loss calculation and recording** | LC | 2 |
| UC FM-3: **Preventive maintenance** | PM | 3 |
| UC FM-2: **Outage Diagnosis** | ODiag | 4 |
| UC VQ-1: ***LV Grid Monitoring*** | GMon | 5 |

### 4.3.1 Grid Monitoring (GMon)

The Release 1 GMon application is executed by the DSO, who specifies a LV grid area and a time interval [t1, t2] in the past and then uses measured or OGM-calculated average voltage values over 15min intervals in order to provide the following output:

- Time Series of 15min average voltages at all grid nodes in the selected LV grid area over the full time interval
- List of grid nodes, which have been exceeding configurable limits of 15min average voltages
    - frequency of over- and under-voltages at these nodes in the selected time period
- 95% quantiles of 15min average values over a 1-week time-window and evolution of these quantiles over time. Release 1 uses a sliding window shifted by one day each time.
- number of 'strong' sags and swells for each 'measured' grid node for each day; the definition of these events is chosen according to smart meter event definition and inverter disconnect event definitions.

The above outputs are written back to the ICT Gateway (so that the GUI application can subsequently visualize them together with average voltage profiles over time at any selected grid node).
The following measurement data and events are used in the Release 1 application implementation:
**From Inverter Subsystem:**

- 5-minute-average values of all line to neutral voltages with a time stamp
- Inverter disconnection from the grid due to a violation of one of the voltage trip limits generates an over-/undervoltage event message

**From AMI and EM subsystem:**

- 15-min averages of phase-to-neutral voltages (which for Release 1 will be lumped by the ICT GW to a single value)
- Short under-voltages and short over-voltages with a duration of 1 second and more

**From the OGM**

- GMon will make use of the OGM in order to calculate voltages at all grid nodes. This calculation however is transparent to the application as it is triggered by the ICT Gateway. GMon will just receive a 'complete' set of voltage values, irrespective whether measured or calculated.

Future Releases of the GMon application will have extended features based on the assessment of the Release 1 implementation. Candidates include a real-time execution mode for monitoring, per-phase analysis of voltages, elimination of time periods of abnormal grid operation in maintenance or fault cases.

### 4.3.2 Loss Calculation (LC)

The LC application is executed by the DSO, who specifies a LV grid area (by a trafo ID) and a time interval [t1,t2] in the past (e.g. 'last month'). It then uses measured or OGM-calculated average active and reactive energy values over 15min intervals. For each time interval, 4 values for each customer grid node and for the substation are specified: consumed active energy, generated active energy, consumed reactive energy, generated reactive energy. It then provides the following output:

- Total energy values for the time interval [t1, t2]
    - Total accumulated active energy loss in the LV grid part below the trafo LV busbar

    - Total energy that has been flowing through the LV trafo in the time period
- For each 15min interval:
    - Average active power loss in the LV grid part below the trafo LV busbar
    - Average active power passing through the LV trafo in that period
    - Average reactive power loss in the LV grid part below the trafo LV busbar
    - Average reactive power passing through the LV trafo in that period

If the LC calculation can obtain quantification of measurement errors from the ICT Gateway, then it in addition provides confidence intervals for all the above outputs.

The above outputs are written back to the ICT GW (so that a GUI application can subsequently visualize them over time).

The following data from the subsystems is thereby used in Release 1. The LC application however does not need to know which type of measurement device has provided the measurements; the ICT Gateway represents the values in a harmonized form (15min values) in a single format to the LC application.

- From Inverter Subsystem: 5-minute-average values of active power generation
- From AMI and EM subsystems: The Smart Meters can be configured to provide different values. We assume a configuration that provides values of active and reactive energy for 15min intervals. These values are accumulated over the 3 phases and uploaded in batches by the Smart Meter to the Head-end system every 6 hours (for the EM Headend, every 10-20min). From the head-end system, they will be pushed to the ICT Gateway.

The Release 1 LC implementation is implemented based on adding and subtracting energy or power values, see the ‘simple’ comparison method introduced in [10]. Future releases may use the measured or calculated currents as alternative method to calculate losses, see second method including directions for confidence intervals [10]. Furthermore, the treatment of non-aligned measurement intervals is another candidate feature for future releases.

### 4.3.3 Outage Detection (ODet)

The ODet application is triggered by an event from any measurement devices or by a request from the DSO entered via the GUI. The ODet application then creates the following result for the inspected LV grid area:

- For each grid node in the LV grid area, 3 values are generated:
    - Probability the grid node has an ICT outage
    - Probability that the grid node has a power outage
    - Number of phases that are affected by the power outage
- Furthermore, the application may create an ‘Outage detected’ event as output.

The above outputs are written back to the ICT Gateway (so that a GUI application may subsequently visualize them over the LV grid topology, e.g. by different colours in the grid visualization).

The following data from the subsystems is thereby used in Release 1. The ODet application, however, does not need to know which type of measurement device has provided the measurements; the ICT Gateway represents the values and events in a harmonized form in a single format to the ODet application.

Inverter Subsystem:

- 5-minute-average values of all line to neutral voltages.

- Reactive request by the ODet application to the most recent value of generated power.
- Inverter disconnection from the grid due to a violation of one of the voltage trip limits
- Inverter Headend not reachable: this event is created by the ICT GW adapter upon failure of the TCP socket between ICT Gateway and Solarweb.

AMI Subsystem:

- Average voltage for each 15min interval (periodically provided every 6hours together with the energy values). This data is pushed from the AMI Headend to the ICT Gateway.
- Reactive request to the most recent 15min value of average voltage value on each phase.
- Missing Phase Fault Event.
- Last Gasp Alarm.
- HE not reachable: This event is created by the adapter in the ICT GW if the TCP connection to the Headend fails.

EM Subsystem: Not used for Release 1 ODet.

Future releases of ODet will focus on improving the detection accuracy and the time to detect an outage.

### 4.3.4 Outage Diagnosis (ODiag)

ODiag will determine and localize the cause of an outage. ODiag is triggered by a detection event of ODet. The Release 1 version of ODiag focuses on short-circuit faults. It will request additional measurements (1second values of voltages, and in case of the substation also currents) from the ICT Gateway. The location and behaviour of the fault is assessed by processing data gathered from measurement devices, those who are reachable, and deploying methods for short-circuit impedance calculation to narrow down the possible locations (branches) of the fault. Also, the KPIs to assess the severity of the outage, customers affected and its duration and corresponding energy not supplied are also calculated and presented. The following output is provided:

- A list of grid locations (substation, cables, junction boxes) and the likelihood that the cause of the outage is associated with this grid location
- The timestamp at which the short-circuit fault started to become active

These results are written back to the ICT GW. In case that during further executions, more data is available that changes any of the location probabilities or cause probabilities substantially, ODiag writes an updated diagnosis output back to the ICT GW.

ODiag will use the following data from Subsystems in Release 1:

- Inverter Subsystem: not used in Release 1 ODIag
- AMI Subsystem and EM Subsystem:
  - Reactive request to the one-second values of phase-to-neutral voltages (as recorded in the local ring buffer periodically, or as recorded triggered by a voltage drop event)
  - At Substation only: reactive request to the one-second values of the currents on each phase (as recorded in the local ring buffer periodically, or as recorded triggered by a voltage drop event)

### 4.3.5 Preventive Maintenance (PM)

Preventive maintenance is a set of actions taken regularly on a particular device in order to lessen its likelihood of failure. PM application targets usage of measurement devices to assess condition of equipment installed in distribution grids i.e. transformers and cables. The Release 1 is focusing on proactively schedule maintenance of substation transformers operating in periodically high stress conditions due to increased penetration of converter based renewables, new type of loads such as electric vehicles, heat-pumps, etc. The PM application runs periodically to assess the asset condition and health indices. The PM is evaluating the relative loading of the transformer, local measurements such as oil and ambient temperature and the current total harmonic distortion (THDI) based on a set of rules that accounts for configurable thresholds and time durations. The PM is then estimating the relative aging of transformer using a set of historical data and order a maintenance visit or reschedule the existing plan when this value is higher than a configurable target value. The main working assumptions for Release 1 are as:

- secondary substations are equipped with oil-filled transformers;
- oil and ambient temperature sensors close to transformer tank are installed or will be deployed at the substation;
- temperature sensors can be integrated in RTU subsystem so that data is communicated to the ICT GW;
- temperature sensors are integrated in a dedicated temperature measurement subsystem (TMS) when RTU subsystem is not available i.e. only AMI is available;
- Historical of at least one-month data is available from measurement subsystems.

With the data collected by these sensors, PM application will firstly compute the historical relative loading of the trafo. This will already introduce a first understanding of the dissolved gases generated by the usage profile which impact directly the aging curve of the asset. Then a correlation is made with the historical temperature records and a ration between loading and temperature is calculated so that some thresholds are also imposed. The THD is then also analysed so that eventual problems can be detected in their early state and before cause any outage.
The next Releases for PM will account for an automatic triggering of PM using the Occurrence Counter Logger for THDI from AMI and RTU as well as inclusion of voltage measurement in computing the relative aging indices.

### 4.3.6 Control Coordination Application

The control coordination is managed in the Automatic Voltage Regulation (AVR) app. The goals of this application are

- Fair distribution of grid support to counteract over-voltage due to multiple generators along feeder, maximizing DER hosting capacity without grid reinforcement
- Fair distribution of grid support to counteract over-voltage due to multiple generators along feeder, utilizing controllable storage
- Reactive power balancing below (secondary) substation to prevent transformer overloading

The Release 1 version of AVR focuses on these goals in the priority shown. When activated, it will request additional measurements (1-second values of voltages, currents, active/reactive power flows) from the ICT Gateway. The AVR app solves one or several optimization problems involving relevant performance metrics, such as:

- Overall renewable capacity
- Fairness of distribution of delivered energy among generating units
- Cost of data acquisition and actuation
- Balanced reactive power flow
- Power losses

while avoiding violating relevant constraints, e.g., production/consumption dynamics and voltage limits. The following output is provided:

- A list of power reference curves to be transmitted to local inverters (PV and storage, if available) in the grid
- Timestamps at which the power references shall become active

These results are written back to the ICT GW. Grid monitoring data is subsequently requested from ICT GW until it is confirmed that the voltage quality meets the correct specifications.

The design of the Release 1 AVR application is still in progress, so more details will follow in future publications.

# 5 Final Net2DG Communication Network Architecture

This chapter introduces the final network communication architecture, and is based on the previously presented architecture already shown in Deliverable 1.1 [1] and Deliverable 1.2 [2]. As the work presented in this has progressed since then, this chapter focuses mainly on describing the high lights, assumptions and modifications since the two deliverables have been written.

The final high level architecture is shown in Figure 4. This is briefly described in the following, while keeping the more detailed descriptions of the realizations in field tests and test bed to later sections. The basic principle behind the concept is that all Net2DG interaction happens through subsystem Head End (HE) connection points, which simplifies the interaction with devices within a subsystem to the ICT Gateway as functionality as device discovery, device authentication and authorization etc., are handled by the head end. The ICT Gateway simply needs to interact with the head end system.

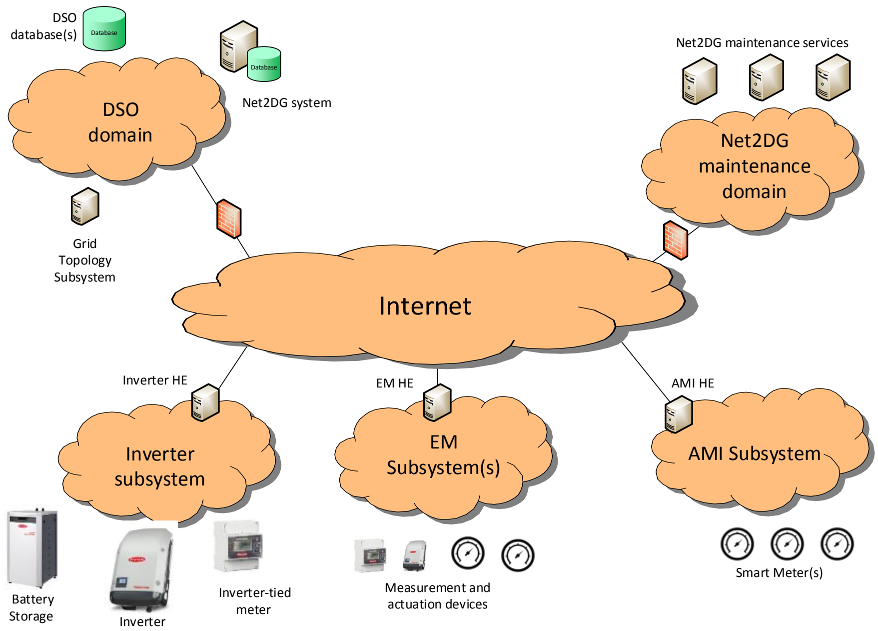


**Figure 4: Generic Communication Architecture in Net2DG**

In the final version of the communication architecture as shown in Figure 4, PV Inverters can be accessed via an interface to a web based Inverter headend. This interface simplifies the technical interaction between Net2DG and multiple inverters, which otherwise would not have been easy to discover, authenticate and access. The Inverter web Headend will have possibilities to perform active control of active and reactive power flow (Q and P) as well as maintaining a constant power factor. In this context, it will act as an aggregator between the ICT gateway and the PV inverters that are organized in groups. Details of the functions and interfaces to this subsystem are described in details in paragraph 3.3 of Deliverable 3.1 [4].

The AMI offers a web interface through the AMI Headend that allows interaction with the smart meters as well as fetching data collected automatically in the internal AMI network. The AMI network may constitute a hierarchy of networks of different types and with a large variety of performance. In the case of Net2DG the project will rely on a system which relies on a low data rate radio mesh based network, which leads to challenges in terms of internal subsystem delays and update frequencies. More details of this subsystems functionality and interface are found in paragraph 3.2 in Deliverable 3.1 [4].

More EM's may be utilized for data access (e.g. from substation measurement devices or mobile PQ measurement devices) and for actuation (e.g. for street light activation and control). The EMs access the local measurement or actuation device over a local network of device specific type. An EM HES will be implemented to provide a similar interface to the various distributed EM's in the field. The functionality and interfaces to the different types of EM's are found in paragraphs 3.5, 3.6, 3.7 in Deliverable D3.1 [4].
A grid topology system HES will be developed to allow the grid topology to be accessed by the Gateway. The interfaces and functionality to this particular subsystem is found in paragraph 3.8 of Deliverable 3.1 [4].

# 6 Deployment Architectures

This chapter focuses on the realizations of the architecture given in Chapter 5. First, a brief overview of the relations between field tests and lab, and how they complement each other are given. This is followed by some level of details of individual realization architectures.

## *6.1 Summary of differences/complementary of site test*

The table below illustrates the main characteristics and advantages/disadvantages of the various field test area as well as the lab, providing an overview of how the different test environments support and complement each other. The summary is covering mainly the Release 1 work and will be further extended in the next period.

| | **Main characteristics** | **Advantages** | **Disadvantages** | **Applications** |
|---|---|---|---|---|
| Danish Field test site | Real context, medium sized grid, containing some PV and Wind Generation, close to 100% Smart Meter Deployment | True behaviour<br>Operational Smart Meter System with close to 100% coverage, including secondary substations | Low numbers of PV in grid,<br>Faults and grid operating conditions not controllable,<br>only very limited possibilities to configure customer owned inverters | LC, ODet, GMON |
| German Field test site | Real context, containing large amount of PV generation | True behaviour,<br>EM devices in the substation and junction boxes,<br>larger number of deployed inverters | Low number of Smart Meters,<br>Faults and grid operating conditions not controllable,<br>only very limited possibilities to configure customer owned inverters | LC, GMON |
| Laboratory | Real time simulation,<br>Small subset of grid, | Possibility to run wide range of operating scenarios in a controlled environment<br>Ability to inject faults in the grid and in the ICT system in a controlled manner<br>Testing ICT Gateway and applications in realistic conditions | Simulated behaviour | ODet, GMon |

**Table 2: Overview of complementarities between field tests and lab tests**

## *6.2 Lab Demonstrations*

This paragraph describes the lab facility architecture that will be used to execute the applications in a safe environment, and which allows to perform validation and tests otherwise not possible in the real world field tests.

### 6.2.1 Overview

The proposed laboratory deployment of Net2DG solutions in the RT-HIL laboratory framework is shown in Figure 5.

The following components are considered for the laboratory implementation:

RT-Grid Simulator – is based on Opal-RT system and contains several modules as: Grid Topology and Parameters, Grid Model, Operational Scenarios, Load Profiles including generation, and triggering of grid events.

VMS-AMI – Virtual Measurement Sub-System for Advanced Metering Infrastructure. It contains several modules namely: Virtual Smart Meters (VSM), Virtual Data Collection (VDC) and Virtual Head-End (VHE).

VMS-EM – Virtual Measurement Unit Sub-System. This sub-system is emulating generic measurement devices such as Remote Terminal Units and PQ measurement units. It also contains dedicated modules as: Virtual Device Measurement (VDM), Virtual Remote Terminal Unit (VRTU) and a Virtual Head-End (VHE).
VMS-INV – Virtual Measurement Sub-System for Grid Inverter emulates the behaviour of the data collection mechanism for Grid inverters by using the following modules: Virtual Grid Inverter (VGI), Virtual Data Collection mechanism (VDC) and Virtual Solar Web (VSW).

GTS – The grid topology subsystem obtains the grid topology information from the corresponding files of the real-time simulator and makes it available to the ICT Gateway.

ICT Network – there are 3 different ICT networks one for testbed management, one for ICT-Gateway to Virtual Measurement Device Communication (using the NS3 emulator), one for Opal-RT to Virtual Measurement Device communication, and a third one for logging and testbed control.

ICT Gateway – The ICT Gateway connects on one side to all Virtual Measurement Subsystems and to the Grid Topology information in the testbed via customized adapters. On the other side, it provides the aggregated and processed data to the application layer.

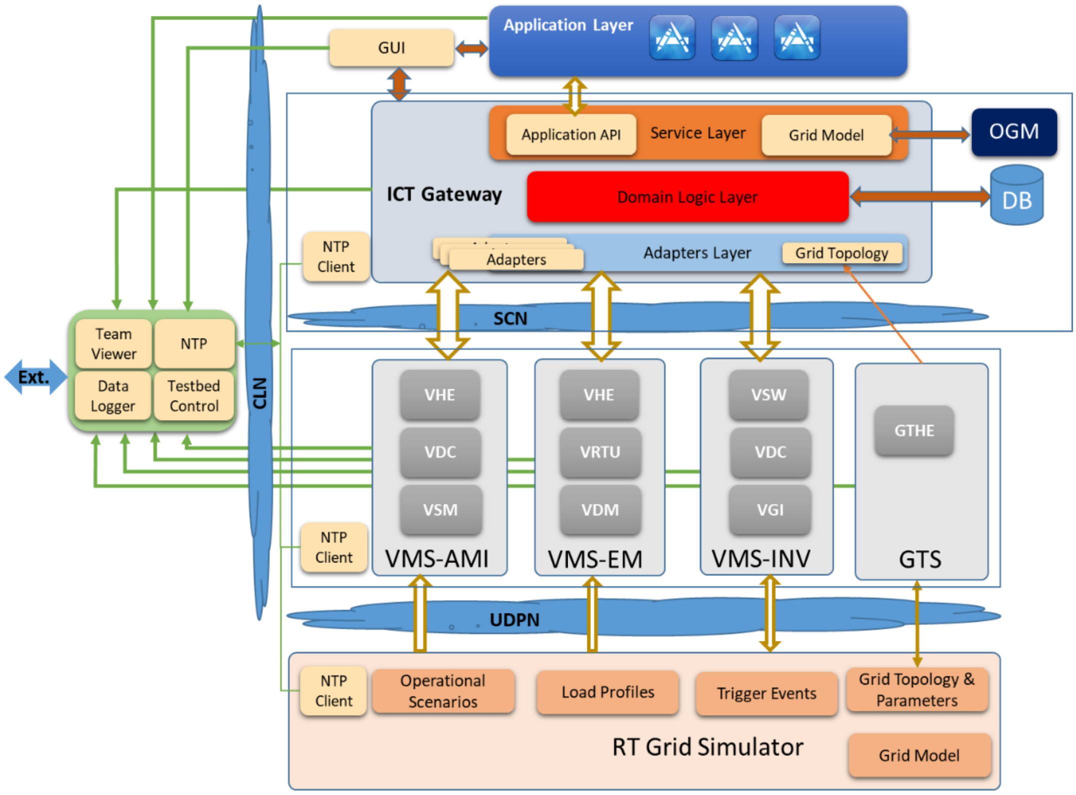


Figure 5: RT-HIL Architecture for Lab Deployment

Application Layer - consisting of target applications and the Graphical User Interface (GUI) as:

- ODet – Outage Detection will be demonstrated in Release 1
- GMon – Grid Monitoring will be demonstrated in Release 1
- ODiag – Outage Diagnosis considered for subsequent releases
- LC – Loss calculation considered for subsequent releases
- OGM – Observability Grid Model
- Control – considered for subsequent releases

There are several ICT Networks in the lab as:

- ICT Network connecting the VMS subsystems to OPAL-RT (UDPN): this a direct Ethernet connection carrying UDP traffic, no network emulator, no other traffic on it.
- ICT Network between VMS subsystems and ICT Gateway Adapters. This network is called Subsystem Communication Network (SCN) and it shall handle network type and data traffic by using a network emulator software. The network emulator is used to inject delays, packet losses and communication outages on individual transport layer connections (i.e. identified by source and destination IP addresses and port numbers).
- Control and Logging Network (CLN): used to setup and start processes on different ICT nodes, NTP synchronisation between nodes; access to or exchange of logging data. This network is the private LAN used in RT-HIL setup and it is not affected by artificial/induced delays and data traffic.

### 6.2.2 Main working assumptions

Several releases are planned during the Net2DG lifetime. Each release is considering the progress and maturity of the developed applications at a certain moment in time. The Release 1 (MS4) is focusing on Outage Detection (ODet), Grid Monitoring (GMon) and GUI. While the other applications i.e. Outage Diagnosis (ODiag), Loss Calculation (LC) and closed loop control will be defined in detail beyond MS4 in subsequent releases.

The main assumptions for Release 1 are as:

- Virtual sub-systems are used for measurement units and data collection mechanisms, i.e. the commercial production systems will not be used as such in the RT-HIL implementation.
- There will be three instance of a virtual measurement subsystem (representing AMI, Inverter and Measurement Unit at substation level e.g. Janitza measurement device, respectively) connecting from different transport layer addresses to the ICT GW. These VMS instances will run on the same host and use the same interface type to the ICT GW. Via configuration files, the individual measurement subsystem can behave slightly different in terms of types of events supported and in terms of averaging intervals for measurements. Multiple instances of the same SW implementation (same source code) will be used for these three measurement subsystems.
- Within one subsystem type (such as AMI, Inverter, …), all emulated measurement devices will behave the same with respect to support alarms, parameters used, etc. There is no per-virtual-device configuration.
- ICT Gateway and application are implemented together on a dedicated platform in the lab (Linux or Windows); the SW implementations will be provided by WP3 (ICTGW, GUI) and WP2 (ODet and GMon)
- The adapters in the ICT Gateway for applications are customized to accommodate the available RT-HIL infrastructure in the lab
- A simple grid topology is used (e.g. single feeder with a few branches below). The GTS will extract the grid topology information for the ICT GW from the OPAL-RT topology.
- UDP will be used to send measurements from OPAL-RT to the Virtual Measurement Devices.
- TCP will be used for the connection between ICT GW and virtual measurement devices in the testbed.
- In case of an ICT outage (which virtual measurement devices will notice by failures of the TCP connection to the ICT GW), measurement devices will continue to take measurements and buffer them locally and retry to open a new TCP connection in regular intervals
- After a possible 'last gasp' alarm (if activated in config file for a PoM), measurement devices will stop communicating when there is a power outage at their Point of Measurement – they will completely stop taking measurements and only resume when the power at the PoM is re-established.
- Inverters and Smart Meters always represent different PoMs, even if they are co-located at the same customer

## *6.3 Danish Field Trial*

Figure 6 shows the modified deployment scenario for TME for Release 1. TME already has a full-scale smart meter rollout in place including CT meters at the substation. The Net2DG field trial will use a small part of the distribution grid i.e. one substation with particular focus on a selected feeder. Data from the smart meters in this area will be provided via the AMI HES, which also provides data collection from substation monitoring devices. Communication to smart meters are via RF Mesh or 2G communication. RF Mesh meters are collected by a concentrator, which in turns is connected via optic-fiber or 3G.

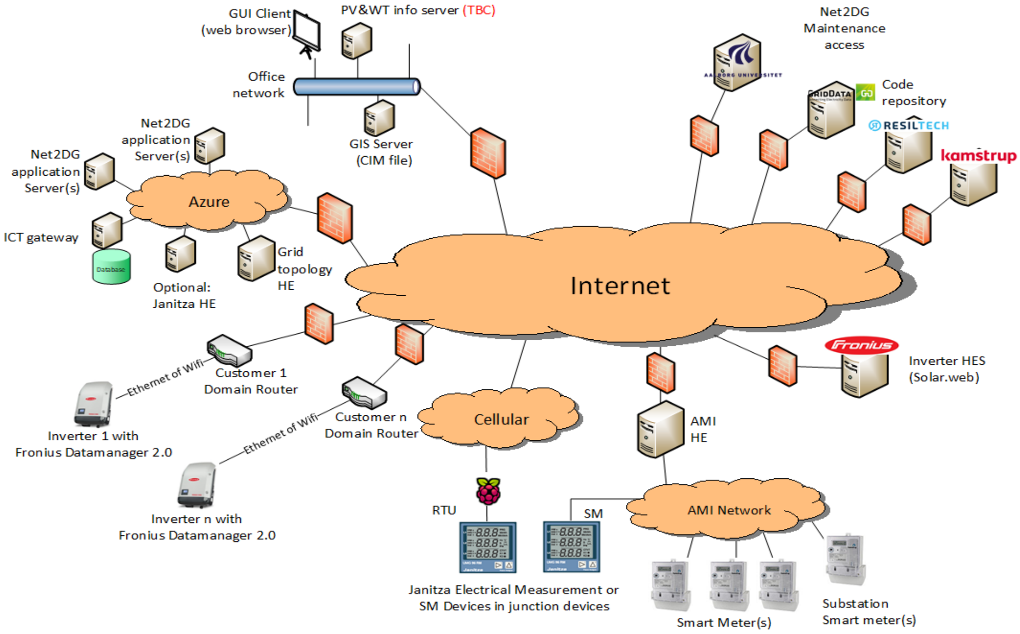


**Figure 6: Deployment variant for TME field trial**

The grid topology is accessed via a dedicated topology HES that access and interacts with a CIM XML formatted file containing the topology. The central part of Net2DG will be executed on a Virtual Machine provided by TME which solves several issues and concerns regarding security and any potential violation of handling of sensitive data. The VM provider is Microsoft and the platform is Azure, which as base fulfils the requirements for handling data securely. Further, using such platform allows flexible processing and memory extensions as needed if the GW and/or subsystem HES turns to need more resource demanding than planned, or for later scaling up the system.

## *6.4 German field trial*

The German field trial in Release 1 will use a single LV grid area with 73 customers. It will use three data sources for the observability applications:

1. Grid Topology Subsystem: The data from the GIS system combined will be combined with data from the customer information database by the Grid Topology Headend.
2. Electrical Measurement (EM) devices at the substation and at about at least 5 junction boxes will be deployed. Devices from the vendor Janitza will be used in this installation.
3. Measurement data from 2-3 customer installations will be connected via the Solarweb server.

Due to the delay of Smart Meter deployment in Germany, Release 1 deployment will not use any smart meter data. Instead, a number of EM devices will be deployed at junction boxes.

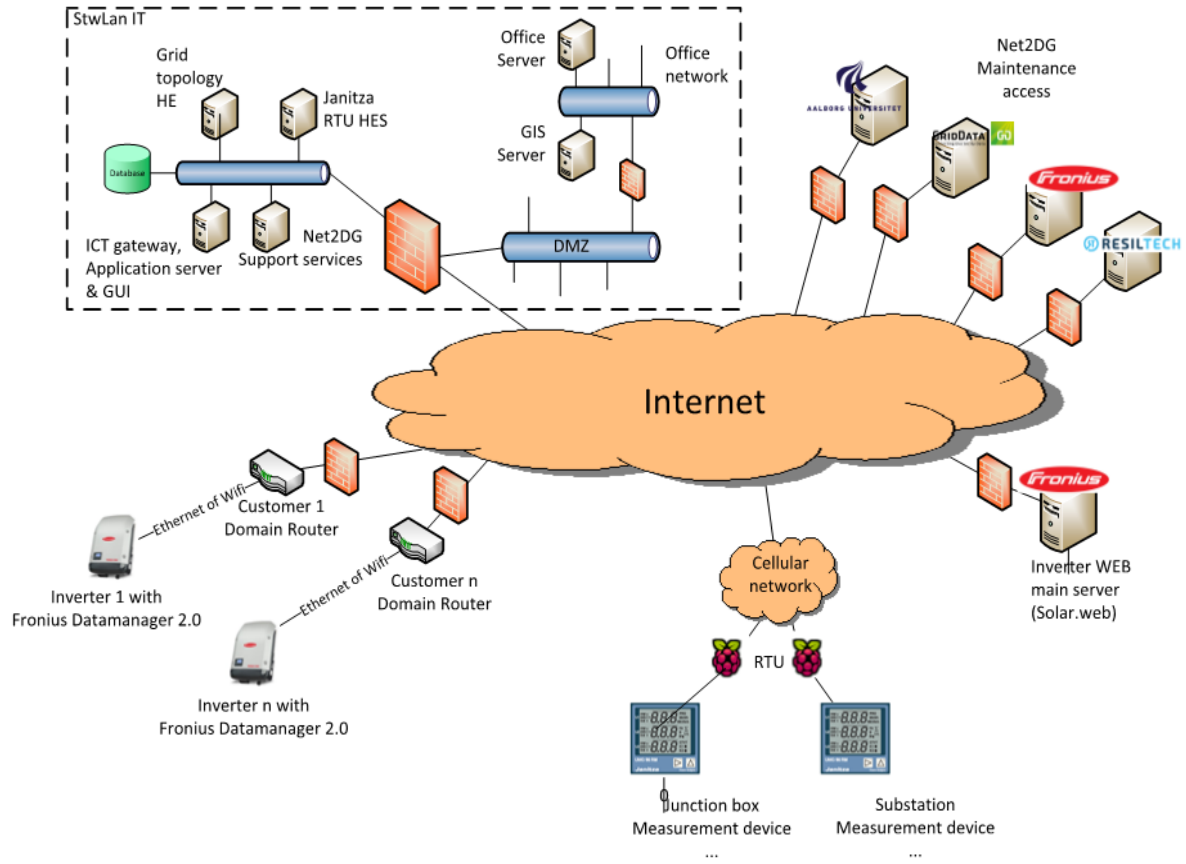


**Figure 7: Deployment variant for Stadtwerke Landau field trial**

The deployment scenario for Stadtwerke Landau is shown in Figure 7: Deployment variant for Stadtwerke Landau field trial The Net2DG developed headend servers, Grid Topology Headend and EM Headend together with the ICT Gateway and the applications are being deployed at a subnet at Stadtwerke Landau (upper left in Figure 7: Deployment variant for Stadtwerke Landau field trial). Data connections to already existing inverters at customer installations (lower left) are being established, so that the existing inverter Headend (Solarweb server of Fronius) retrieves the corresponding data. The EM, here Janitza, devices will be deployed at substations and junction boxes and the data is obtained from RTUs implemented by Raspberry Pis that then connect via cellular networks to the EM Headend.

Focus of the Release 1 deployment at Stadwerke Landau will be on the applications GMON and LC.

# 7 Summary and outlook

The Net2DG architecture has been developed in its initial version [2] based on a prioritized list of use-cases which are summarized in Chapter 2 of this deliverable. Since the initial version, this architecture has been subject to several delimitations and modifications. Chapter 3 shows the updated high-level system architecture of the Net2DG solution which is centred around the ICT Gateway, that acts as a mediator between data and actuation subsystems and the Net2DG applications. The Net2DG observability and control coordination applications are summarized in Chapter 4. Two different grid models are used for the execution and assessment of these applications, respectively, which are also summarized in Chapter 4. This is supported by Chapter 5 where the final Net2DG Network Communication Architecture is high-lighted. In chapter 6, the deployment architectures for laboratory demonstrations and for the two field trials in Net2DG is identified and they will be used as a basis for several releases during the Net2DG lifetime. Main working assumptions are identified and formulated.

Deviations from the presented base line architecture may occur after completion of Release 1 in order to accommodate the ICT Gateway and Application Layer in the laboratory framework and in the two field trial deployments. However, the targeted functionalities and their performance will not be affected. This will pave the way for future implementations in the Net2DG lifetime where expansions of the applications and grid models will be obvious paths to pursue.

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