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D3.1 – Design specification for network observability

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Contributions of partners

Partner	Contribution
UdG	Owner, main editor and integrator. Specification of EF, CEF, NTLFDA, FDA WAMS, PMU and PQM.
UPC	Specifications of PED.
SIN	-
JR	-
ICOM	Deliverable review.
EYPESA	Observability specifications from operational point of view. Specifications of legacy systems (AMI, SCADA).
CS	Specification of WAMS, PMU, PQM, and FDA. Deliverable review.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773715

Table of contents

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Acronyms and abbreviations

AMI	Advanced Metering Infrastructure
CEF	Critical Event Forecaster
DCU	Data Concentrator Unit
DMS	Distribution Management System
DSO	Distribution System Operator
EF	Energy Forecaster
ESB	Enterprise Service Bus
FDA	Fault Detection Application
GM	Grid Meter (meter installed at DCU)
GW	Gateway
HLUC	High Level Use Case
ILEM	Intelligent Local Energy Manager
LV	Low Voltage
LVGOI	LV Grid Observability Infrastructure
MAPE	Mean Percentage Error
MDC	Meter Data Collector
MDMS	Metering Data Management System
NTLFDA	Non-Technical Losses and Fraud Detection Application
PED	Power Electronics Device
PMU	Phasor Measurement Unit
PRIME	PoweR line Intelligent Metering Evolution
PQM	Power Quality Monitor
RDB	Reading Data Base
RMS	Root Mean Square
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SHA	Self-Healing Application
SM	Smart Meter
SS	Secondary Substation
UC	Use Case

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Executive Summary

The RESOLVD project has the objective of increasing the hosting capacity of renewable energy sources in Low Voltage (LV) grids by increasing the flexibility of these grids. Hence, RESOLVD aims to increase the flexibility of LV grids by developing solutions that increase the observability of LV grids and solutions that exploit this enhanced observability to enable an active and automatic management of the grid at LV.

In this context, the LV observability infrastructure has the objective of gathering the required information from the LV grid with adequate resolution, so as other systems can perform actuations on the LV grid that increase its efficiency and resilience.

This report aims to describe the design specifications of the LV observability infrastructure that will be developed in the project. In particular, Section 1 describes relevant High Level Use Cases (HLUC) identified by RESOLVD and specifies an architecture that reflects grid operation according to these use cases. Section 2 briefly presents the data requirements of the HLUCs. Section 3 describes the requirements of the applications and functions that will operate (or help to operate) the grid according to the identified HLUCs. Section 4 presents the specifications of the main subsystems of the LV grid observability infrastructure, the monitored variables, and an overview of the way these subsystems will be integrated.

This document complements deliverables D1.2[1] and D1.3[1], which describe the functional and interoperability requirements of the individual components, respectively.

[1] Public deliverables will be accessible in https://resolvd.eu/documents/

1. Introduction

The RESOLVD project has the objective of increasing the hosting capacity of Low Voltage (LV) grid (namely variable generation) by increasing the flexibility of the grid. This increase of flexibility will be achieved by using Power Electronics Devices (PEDs) and switchgears that will enable dynamic reconfiguration of the grid, and software tools that will provide decision support to operate the grid in an efficient and safe manner.

In particular, the RESOLVD project has identified the following operational High Level Use Cases (HLUCs):

- *HLUC01: Prevention of congestion and over/under voltage issues through local storage utilization and grid reconfiguration.* It aims to forecast possible congestion and under/overvoltage situations and take the necessary actions to prevent or mitigate them. These actions include import and export of power from local storage systems and grid reconfiguration.
- *HLUC02: Voltage control through local reactive power injection.* It aims to control voltage by importing or exporting reactive power from local storage devices, using Power Electronic Devices (PEDs).
- *HLUC03: Improving power quality and reducing losses through power electronics*. It aims to control power quality. In particular, it comprises the compensation of reactive power, unbalanced currents and harmonics through actuation of PEDs.
- *HLUC04: Local storage utilization to reduce power losses*. It aims to forecast energy demand and supply, and modify the load profile of controllable units in order to minimise the energy losses of the system.
- *HLUC05: Self-healing after a fault*. It aims to detect, diagnose and locate faults in the grid and take the necessary actions for minimising the effects of the fault. It includes grid reconfiguration for isolating the fault.
- *HLUC06: Power management in intentional and controlled-island mode*. It aims to predict energy demand and supply in a grid island, and consequently, take the necessary actions to ensure power balance.
- *HLUC07: Detection and interruption of unintentional uncontrolled island-mode*. It aims to detect unintentional grid islands, e.g. due to a zero power flow between the main grid and the grid island, and take the necessary actions to interrupt the islanding.
- *HLUC08: Detection of non-technical losses (frauds)*: It aims to monitor individual and aggregated power consumption to detect fraud.

From these HLUC, functional and operational specifications of involved actors have been described in D1.2 and derived Primary Use Cases (PUCs), described in D1.1, will be detailed according to the SGAM (Smart Grids Architecture Model) methodology in the D1.3 and security issues D1.4.

The tools and devices introduced by RESOLVD aiming to fulfil the objectives of these HLUCs need accurate and timely information about the grid. Therefore, RESOLVD also has the objective of developing new and integrating existing technologies in order to increase grid observability by providing adequate information to the tools that handle grid operation. This set of integrated subsystems and technologies is referred to as **Low Voltage Grid Observability Infrastructure (LVGOI)**. The LVGOI aims to provide accurate information in time and geospatial resolution, needed to operate a LV grid with great presence of distributed (renewable) generation in an efficient manner and respect the safety and security related concerns.

Figure 1 illustrates a high-level view of the RESOLVD architecture. Mapping of main actors in domains and zones (SGAM smart grid plane) can be identified in the figure. It also differentiates between legacy systems (depicted in blue) and new components delivered by the project (depicted in green).

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The LVGOI comprises of all components responsible for (i) monitoring and measuring of grid variables, (ii) actuation (PED and switchgear), (iii) data gathering and management, and (iv) support components enabling integration and communication.

The subsystems that compose the RESOLVD LVGOI can be classified as follows:

- **Management systems:** those that gather, organise, and manage data
  - Wide Area Monitoring System (WAMS)
  - Advanced Metering Infrastructure (AMI)
  - Supervisory Control and Data Acquisition (SCADA)
- **Instruments and Metering devices:** those with measurement capabilities
  - Phasor Measurement Unit (PMU)
  - Power Quality Monitor (PQM)
  - Smart Meter (SM)
  - PED

The aim of this report is to describe the LVGOI's components specifications needed to provide required information to other subsystems of the RESOLVD architecture, as well as, identify the required data sources and their capabilities and constraints, and determine the conditions for its availability. The main objectives can be split up as follows:

- Describe data requirements according to RESOLVD HLUC
- Describe the requirements of DMS applications and functions for the LVGOI
- Describe the proposed LVGOI
- Describe the (main) components integrating the LVGOI

Section 2 of this report presents the data requirements derived from the HLUCs. Section 3 describes the requirements of the applications and functions that will operate (or assist the operation of) the grid according to the HLUC. Section 4 presents the individual specifications of the main subsystems of the LVGOI, the monitored variables, and the integration of these subsystems. This report is complementary to deliverables D1.2[2] and D1.3[2], which describe the functional and interoperability requirements of all components of the RESOLVD project, respectively.

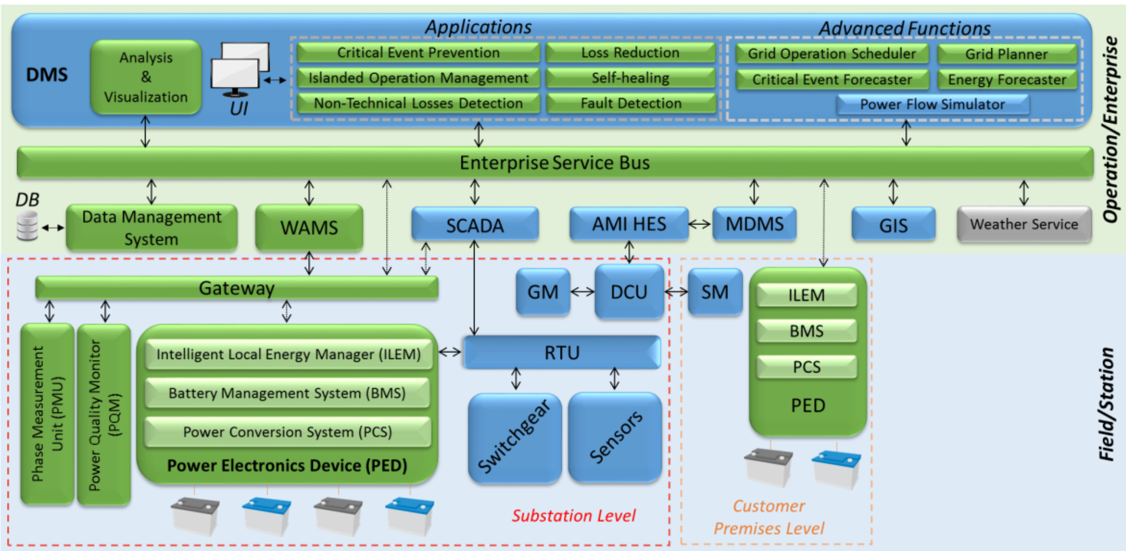

Figure 1. RESOLVD architecture (component view)

[2] Public deliverables will be accessible in https://resolvd.eu/documents/

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2. Data requirements according to HLUCs

The LVGOI has the objective of gathering data about the grid to allow a more efficient and safe operation of a LV grid with a high share of renewable generation (mainly photovoltaic power). This imposes new requirements in terms of sampling frequency and spatial/assets observability in order to enable the Distribution Management System (DMS), and other applications and subsystems to perform the necessary actions to react to specific situations as explained in the use cases described in deliverable D1.1.

The observability needs, in terms of time resolution, derived from the aforementioned HLUCs are summarised in Table 1.

Table 1. RESOLVD observability requirements

HLUC	Observability requirements
01	At the grid buses: – Consumption and generation with sampling period equal to or lower than the operation schedule time slots (i.e. 1h).
02	At the acting/control point: – Voltage with sampling period lower than 10 minutes[3].
03	At the acting/control point: – Reactive power (or power factor) – Voltage harmonics with sampling period lower than 10 minutes[4]. – Three phase currents (or power flow).
04	At the grid buses: – Consumption and generation with sampling period equal to or lower than the schedule time slots (i.e. 1h).
05	At substation and selected points (WAMS design): – Fault Detection: Voltage (RMS) every 10ms, at least, to assure observability of faults (voltage sags and swells) according to IEC61000-4-30:2015[5]. – Fault Isolation: Isolation requires redundancy. It means that multiple instruments are required and/or alternatively accurate information of the grid (topology and physical parameters). Location will depend on grid topology and exploitation.
06	At grid buses: – Consumption and generation on grid buses with sampling period equal to or lower than the schedule time slots (i.e. 1h).
07	At selected acting points in the grid (design dependent): – Voltage with a sampling period enough to guarantee the reconnection to the main grid, i.e. few seconds.
08	At consumption points and secondary substations:

[3] According to UNE-EN 50160 (2011), 95% of voltage for a week, averaged every 10 minutes, should be within $\pm 10\%$ of its nominal value.
[4] According to UNE-EN 50160 (2011), 95% of RMS value of each harmonic for a week, averaged every 10 minutes, should be lower than specific values.

[5] https://webstore.iec.ch/publication/29760

	– Individual consumption at customer level (anonymized) and aggregated consumption at grid level. No specific timer resolution is required, that provided by smart meters is enough (15 min – 1h)

3. Observability requirements for the DMS applications and functions

This section includes specifications on how actors integrated in the DMS consume field data. Most of the applications in the DMS (Figure 1) do not consume directly field data. Such applications include Grid Operation Scheduler, Grid planner, Power flow simulator, Loss Reduction, Islanded Operation Management, Self-Healing. However, they require inputs from the Energy Forecaster (EF) and other applications, which need access to acquired field data to carry out computations.

Thus, DMS observability requirements are reduced to specifications of four main applications, directly operating with field data. These are EF, Critical Event Forecaster (CEF), Fault Detection Application (FDA) and the Non-Technical Loses and Fraud Detection Application (NTLFDA). The specifications for each are detailed in the following subsections.

3.1. Energy forecaster

The EF is a machine learning module able to learn numeric models that predict energy demand and generation within a certain error based on the evolution of the variable to be predicted and incorporating information from other independent variables. Thus, it has two basic operation modes: training and forecasting. Training is performed to learn the forecasting model. It means the selection of variables, topology proposing, parameters adjustment, etc. In the forecasting operation mode, the module provides forecasted values for a given time horizon and resolution (e.g. hourly production for the next 24 hours, that is a 1h resolution and 24h time horizon). The implementation and performance of this application will be reported in D3.2[6].

3.1.1. Preconditions

In order to build the forecasting models, it is compulsory the availability of historical data for a sufficient period, to gather variability on consumption/production at the prediction point. Such data includes the predicted variable (demand/generation), but also other independent variables directly correlated with demand/generation as weather information (temperature, irradiance, irradiation, etc.) with the same time reference.

Pre-processing and cleansing techniques are needed to ensure good data quality. In RESOLVD, data will be accessible from the Metering Data Management System (MDMS) via the Enterprise Service Bus (ESB).

Additional data treatment needed for the forecasting algorithms may be included as part of the forecasting software.

In order to exploit the forecasting models, on line data corresponding to the same variables selected for building the models is need.

3.1.2. Input data specifications

Data nature and origin:

- **Training mode:** consumption / generation, weather data (irradiance, temperature) equally sampled (typically hourly) depending on detail of the analysis requirements and with a common time reference. All these data will be stored in the MDMS. Optionally, calendar data (for demand forecasting).
- **Forecasting mode:** same variables used as inputs for training, weather forecast, directly provided by weather forecast agencies.

[6] Public deliverables will be accessible in https://resolvd.eu/documents/

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Dependence on data format:

- Table-like (variables in columns and observations in rows) organisation: Each row has to refer to the same timestamp (typically 1 hour). Current formats accepted: DB tables, csv, arff, xls, json.

3.1.3. Outputs

The EF after training produces a model with the associated performance indicators, e.g. Mean Percentage Error (MAPE) that will be managed internally.

In the forecasting mode, the module uses the model and gives predictions:

- The predictions are numeric values (forecasting data vector). Optionally can be exportable to .csv files or JSON/XML structures.

3.2. Critical event forecaster

The CEF is a machine learning module able to learn numeric models capable to predict critical events such as congestion and over/under-voltage situations within a certain error based on historical information of voltages gathered from SMs and power flow simulation results based on forecast energy consumption and generation provided by the EF.

CEF has two basic operation modes: training and forecasting. Training is performed to learn the forecasting model. It means the selection of variables, topology proposing, parameters adjustment, etc. In the forecasting operation mode, the module provides a forecast of critical events for a given time period and resolution.

The implementation and performance of CEF will be reported in D3.2[7].

3.2.1. Preconditions

In order to build the forecasting models, it is compulsory to feed them with historical data during sufficient period, with the aim to gather variability on voltages at the prediction point.

Pre-processing and cleansing techniques are needed to ensure good data quality. In RESOLVD, data will be accessible from MDMS via the ESB.

Additional data treatment needed for the forecasting algorithms may be included as part of the Forecasting module.

In order to exploit the forecasting models, data corresponding to the same variables selected for building the models is need, i.e. SM voltage data.

3.2.2. Input data specifications

Data nature and origin:

- **Training mode:** SM voltages, which will be stored in the MDMS.
- **Forecasting mode:** SM voltages (last 24h available data), power flow simulation results (lines loading and bus voltages) using EF forecasts

Dependence on data format:

- Table-like (variables in columns and observations in rows) organisation: Each row has to refer to the same timestamp (typically 1 hour). Current formats accepted: DB tables, csv, arff, xls, json.

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3.2.3. Outputs

CEF after training produces a model with associated indicators, e.g. MAPE, that will be managed internally.

In the forecasting mode, CEF provides critical event forecasts using the trained model. The predictions are binary values (critical event or not) with the associated timestamp. Forecasts can be exported to .csv files or JSON/XML structures.

3.3. Fault detection application

Given the instantaneous conditions dynamicity due to the proliferation of distributed energy resources and aims to maximally utilize the power system infrastructure by operation closer to the margin, unexpected outages caused by faults or short circuits are of increasingly frequent occurrence. The capability of promptly detecting, accurately localizing and autonomously isolating the faulted area allows the speed up of power system restoration and thus enhances system reliability and availability.

The FDA aims to detect, diagnose and localize faults or other grid disturbances characterized by large and sudden variation of load. In general, the following implementation approaches can be distinguished:

- travelling wave methods,
- impedance-based methods, and
- pattern recognition methods.

According to the literature, travelling wave methods offer good performance in terms of detection reliability and location estimation accuracy, and are also not significantly affected by load magnitude variation, current transformer saturation, fault type, and fault resistances. The measurement equipment however needs to support very high sampling rates (in the order of MHz) to detect the wave fronts, which makes the application of this methods unfeasible for the considered measurement equipment (i.e. PMU, PQM, SM).

The impedance-based methods are characterized by low complexity and according to literature offer a fairly accurate localization performance. Their performance is particularly good in cases of grounded power system infrastructure, while their application to isolated and Petersen-coil grounded power systems is a challenge addressed also by the RESOLVD project. Additionally, these methods are highly sensitive to the fault resistance and can yield multiple solutions in highly branched networks. A comparative study of some representative methods is provided in [1], while the application to distribution networks using the PMU measurement infrastructure is presented in [2], [3], and [4]. Note also that fault detection and localization methods developed for transmission networks are not directly applicable, since distribution networks (i) are highly branched, (ii) consist of overhear and underground lines, (iii) have heterogeneous and un-transposed lines, and (iv) include unbalanced loads.

The pattern recognition methods are based on large training databases that contain reference cases for normal, abnormal and faulty power system conditions. Typically, these methods do not need complex formulation, however may require very high quality measurements and are often characterized by high computational complexity. The training sets are also valid only for a particular system configuration. All this imposes several challenges for the application of these methods to distribution networks, since the topology and conditions are highly variable. The focus of RESOLVD project is on the application of multivariate statistical models to the classification of fault type and properties.

The implementation and performance of FDA will be reported in D3.4[8].

[8] Public deliverables will be accessible in https://resolvd.eu/documents/

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3.3.1. Preconditions

The preconditions for impedance-based methods include a priori knowledge of (i) network topology, (ii) network configuration, (iii) line parameters, and (iii) load profiles. For the detection of fault, one PMU may be enough, while for the localization at least two are required. Apart voltage and current synchrophasors measurements, the PMU data message shall as well contain the validity of measurements according to internal estimation algorithm.

The pattern recognition methods will mainly exploit the recognition of signatures characterizing the transient events (i.e. disturbances interrupting quasi steady-state regime). In addition to voltage and current synchrophasors, these techniques could as well exploit raw voltage and current measurement around the detected event or estimates of power quality.

3.3.2.Input data specifications

The main input data to impedance-based and pattern recognition methods are voltage and current synchrophasors, frequency, rate of change of frequency, and power quality. Additionally, the methods also exploit message flags denoting validity of PMU data in terms device synchornization to master clock and estimates validity according to internal algorithm.

3.3.3.Outputs

The FDA automatically detects faults and disturbances of the grid and reports those via ESB to operator user interface, self-healing application and/or geographic information system. The outputs messages of FDA are:

- Fault detection alarm message, containing also an estimate of trigger reliability, exploiting the following contextual information
    - network type (grounded/ungrounded),
    - verification of fault detection with alternative algorithms,
    - number of PMUs serving the area of interest,
    - percentage of PMUs detecting the fault,
    - validity of synchrophasor estimates provided by PMU,
    - precision of load profiles.
- Fault line identification message.
- Estimate fault location (relative to end points of faulted line) message.

3.4. Non-technical losses and fraud detection application

The NTLFDA application is devoted to learn consumption patterns and detect abnormal events in order to alert about possible frauds. Two levels of detection are proposed: (i) at individual consumer level (it aims to detect variation w.r.t. normal consumption), and (ii) energy balance at grid level (comparison of metering at grid level with aggregation of associated consumers).

3.4.1. Preconditions

In order to learn consumption patterns it is compulsory to dispose with historical data from consumption points (smart meters) and grid meters (global meters installed at the location of DCU), with the aim to perform energy balance comparison.

Pre-processing and cleansing techniques are needed to ensure good data quality. In RESOLVD, such data will be pulled from the MDMS, which will be accessible via the ESB.

3.4.2. Input data specifications

Consumption at the smart meters and grid meters available at MDMS

3.4.3. Outputs

The NTLFDA gives for each consumption point, a statistical indicator of the dates when possible fraud occurs and at the grid level, it provides alarms when balance between aggregated values and global meters is greater than the expected technical losses.

4. Specifications of LV network observability subsystems

According to the identification of requirements in the previous section, the LVGOI integrates different application instances that are composed of one or several instruments and a dedicated software. Instead of considering a completely new instrumentation infrastructure an integrated approach is conceived, combining new and legacy components in a way desired by particular application.

This section describes the specifications of the subsystems synthesizing the LVGOI in terms of observability capabilities according to requirements derived from HLUCs listed in Section 2.

4.1. Field data management actors

From the network observability perspective, these actors, or subsystems, are in charge of collecting field data from one or several instruments and distributing it to other actors of the RESOLVD architecture (see Figure 1) through the ESB.

The following subsections include the specifications about how these subsystems collect and provide data access in order to assure data availability in the terms pointed in the previous section.

4.1.1. WAMS

WAMS is a set of server hosted applications that gather, analyse and distribute data from distributed sensors, usually PMUs. RESOLVD is extending the scope of the distributed sensors by including also time-synchronised PQM. Moreover, WAMS usually acquire distributed sensors data from phasor data concentrators. However, RESOLVD proposes extending the purpose of phasor data concentrators to a more generic GW that supports adaptations among message exchange protocols, features different connectivity interfaces (including wireless), or even provides some on-site computation capability. Figure 2 depicts the integration of WAMS, GW, PMU and PQM.

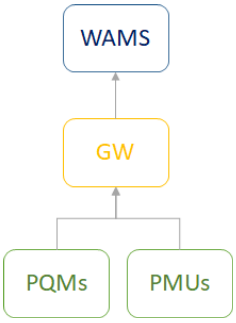

Figure 2. WAMS and PMU-PQM integration diagram of RESOLVD

In the following, specifications related to WAMS with data analytics capability and interface to DMS are provided, while PMU and PQM devices are further discussed in Sections 4.2.1 and 4.2.2, respectively.

In RESOLVD, the role of WAMS is mainly reflected in HLUC05, which consists of detecting and locating grid faults and/or other disruptions. WAMS application is, on one hand, responsible for the collection, verification and storage of all data aggregated from sensors, and on the other hand for the provision of data to dedicated analytics services. These includes observed network segment modelling, historical or live data pre-processing, and real-time detection, classification and logging of events. In case of fault alarm triggering, the FDA is responsible of detailed event analysis and consequential triggering of other systems, such as displaying a notification to the grid operator or transferring the mitigation request further to the Self-Healing Application (SHA).

Table 2 summarises the observability specifications of the WAMS application.

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Table 2. WAMS observability specifications for the LVGOI

<table>
<tr><th>Monitored variable</th><th>Data collection mode</th><th>Updating frequency</th><th>Spatiotemporal coverage</th><th>Data access mode</th></tr>
<tr><td>3-phase voltage magnitude</td><td rowspan="6">As client, subscribed to customized data feed from PMU</td><td rowspan="6">20 ms
(up to 100 ms delay)</td><td rowspan="6">PMU area</td><td rowspan="6">Subscription</td></tr>
<tr><td>3-phase voltage angle</td></tr>
<tr><td>3-phase current magnitude</td></tr>
<tr><td>3-phase current angle</td></tr>
<tr><td>Frequency</td></tr>
<tr><td>Frequency rate of change</td></tr>
<tr><td>3-phase voltage rms</td><td rowspan="5">Request-response or publish-subscribe</td><td rowspan="7">1 s</td><td rowspan="7">PQM area</td><td rowspan="7">Subscription or on demand</td></tr>
<tr><td>3-phase current rms</td></tr>
<tr><td>3-phase active power</td></tr>
<tr><td>3-phase reactive power</td></tr>
<tr><td>3-phase power factor</td></tr>
<tr><td>Harmonics</td><td rowspan="2">Request-response</td></tr>
<tr><td>Total harmonic distortion</td></tr>
<tr><td>Critical event detection</td><td>-</td><td>from 20 ms to 1 s, depending on applied method</td><td>WAMS area</td><td>Upon detection, WAMS notifies DMS (FDA, SHA) via ESB</td></tr>
</table>

4.1.2. AMI and MDMS

The AMI comprises all metering components used to measure consumption and demand at the consumer level. Therefore, it mainly concerns the chain composed by the SM at customers' premises, Data Concentrator Units (DCUs) installed in transformer substations and usually equipped also with a GM, and the infrastructure and software required for the transmission, management and storage of these data also known as Meter Data Collector (MDC). MDC is responsible for managing SMs data and storing them in the corresponding data base or MDMS.

Figure 3 illustrates the architecture of AMI and its components. Currently, SMs measure exported and imported energy and other electric parameters such as power, voltage and current at the customer premises. They usually get measures hourly, but can support higher resolutions and also detection of some qualitative indicators. SMs provide energy reports hourly, usually under a request/response strategy. DCU stores these data and sends them to the MDC, in the DSO premises.

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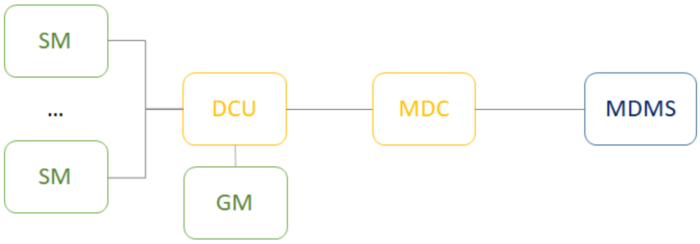

Figure 3. Architecture of AMI components

The MDMS is the actor in the RESOLVD architecture in charge of making data available to the other actors through an Enterprise Service Bus. This data will be the 3-phase active power (consumed and exported), the 3-phase reactive power and the 3-phase voltage measured by each SM and GM. These data will be pulled from the DCU every hour and it will be stored in the MDMS and available to other components under request. Table 3 summarises these analysis.

Table 3. MDMS observability specifications for the LVGOI

Monitored variable	Data collection mode	Updating frequency	Spatiotemporal coverage	Data access mode
3 phase active power per SM/GM	As client, pulling from DCU	Once per hour	All grid (at consumer points) – quarterly, hourly	Upon request
3 phase reactive power per SM/GM	As client, pulling from DCU	Once per hour	All grid (at consumer points) – quarterly, hourly	
3 phase voltage per SM/GM	As client, pulling from DCU	Once per hour	consumer points) – quarterly, hourly	

4.1.3.SCADA

The information of instruments distributed on the grid (substation, relays, protections, etc.) is sent to the operation control room where a SCADA system is used for monitoring and controlling the grid. The SCADA has the mission of aiding in the control the grid, and with this purpose, it has data gathering, storage and visualisation services and allows defining certain properties to data to automatically generate alarms or improve visualisation. Frequency of data refresh depends on many factors such as transmission technologies, priority of variables, etc., but typically, data are updated by the SCADA every 12 seconds in normal conditions. If there are significant variations in the measurements, i.e. abnormal conditions, data are pushed to SCADA with higher frequency and respecting priorities to avoid data congestion.

In general, a SCADA permits to monitor the operation and state of the distribution grid by indicating:

- The state of switches (open/closed or in service/out of service).
- The percentage of saturation (or loading) of lines and other components (medium voltage).
- The voltage, current active and reactive power, and power factor of specific points of the grid (medium voltage).
- The status of the communication system (active, deactivated or if it is well-functioning)

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Presently, the SCADA system in DSO control center primarily enables to supervise the infrastructure at medium voltage level and does not directly control the assets at LV level. With the RESOLVD project introducing LV grid element aimed at flexible balancing of grid state, i.e. the PED, the objectives are to implement coordinated control strategies. This means reconfiguring the grid together with the control of flexible assets. This requires LVGOI to have a limited insight into SCADA operation, which are summarized in Table 4.

Table 4. SCADA: Additional observability specifications for the LVGOI

Monitored variable	Data collection mode	Updating frequency	Spatiotemporal coverage	Data access mode
Switchgear state	As client, pulling from switchgears	< 1 min	All grid (switchgear locations)- at updating frequency	Upon request
PED battery level	As client, pulling from PEDs	< 1 min	All grid (battery locations)- at updating frequency	

4.2. LV grid instruments and metering devices

RESOLVD proposes to enhance grid observability at LV with the incorporation of new instruments such as PMU, but also using legacy instruments such as SM as depicted in Figure 1.

The following subsections include the specifications about the metering capabilities of these instruments in the terms pointed in the previous section.

4.2.1. Phasor measurement unit

PMU is a device that measures electrical waves on an electricity grid, i.e. voltage and current magnitude and angle, frequency and rate of change of frequency. To enable synchronous measurements on a distributed infrastructure, it uses a reference timing source. Unless provided locally, typically the global navigation satellite system is utilized, which allows for time synchronization accuracy under $1\mu s$. The default rate of parameters estimation is once per every period of 50 Hz waveform.

As summarized in **¡Error! No se encuentra el origen de la referencia.**, the PMU data is streamed to WAMS according to IEEE C37.118.2-2011 standard[9] (or alternatively the IEC 61850-90-5 standard[10]).

Besides the metering capability, PMU will feature continuous self-monitoring and diagnostic functionalities in order to identify any abnormalities in parameter estimation algorithms, synchronization to master clock, and communication infrastructure.

[9] IEEE Standard for Synchrophasor Data Transfer for Power Systems," in IEEE Std C37.118.2-2011 (Revision of IEEE Std C37.118-2005), vol., no., pp.1-53, Dec. 28 2011

[10] IEC standard 61850-90-5, (Communication networks and systems for power utility automation- Part90:5: Use of IEC 61850 to Syncrophasor information according to IEEE C37.118", TC57, 2012

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Table 5. PMU measurements specifications

Variable	Sampling period	Resolution	Potential receiver	Sending procedure to receiver
3-phase voltage magnitude	20 ms	IEEE C37.118.1-2011, level 1	WAMS/ DMS (FDA)	PMU publishes based on configuration requested by subscriber
3-phase voltage angle				
3-phase current magnitude				
3-phase current angle				
Frequency				
Rate of change of frequency				

Apart the traditional employment of dedicated redundant connectivity infrastructure, RESOLVD will also investigate the use of wireless connectivity means. Either as primary communication channel for the deployment locations without dedicated connectivity infrastructure, or as a redundant connectivity path for fall-back operation. In particular, the Wi-Fi and LTE technologies will be considered.

4.2.2. Power quality monitor

PQM is a device aimed at permanent monitoring of power quality at all level of power grid, i.e. from production, through distribution and to the final consumer. The lack of information about the supplied power quality can lead to unexplained operational problems and malfunction or even damage of grid assets. Depending on the application, the device performs measurements in compliance with metrology standards and performs analysis according to the prescribed regulatory and compliance framework.

Table 6 summarizes the measurements performed by PQM. In addition to those, internal detection of voltage sag, voltage swell, and phase loss interruption are also supported.

Table 6. PQM measurements specifications

Variable	Sampling period	Resolution[11]	Potential receiver	Sending procedure to receiver
3-phase voltage rms	1 s	IEC 62053-22/23, EN 50160,	WAMS/ DMS	PQM can facilitate either request-response or publish-subscribe principle of measurements publishing via GW
3-phase current rms				
3-phase active power				
3-phase reactive power				
3-phase power factor				
Harmonics		/	DMS	Request-response

For advanced monitoring and control purposes, it is possible to realize custom power quality metrics on top of raw measurements provided by PQM or PMU analog front-end unit. For the

[11] The application of particular standard depends on the application and hardware capability to fulfil the requirements.

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case of PMU, it is even possible time synchronize the measurements of distributed devices and thereby support advanced applications, such as observability of power quality disturbances propagation over the grid infrastructure.

4.2.3.Smart meter and grid meter

Typical SM and GM are capable of providing (locally) instantaneous measurements of:

- Voltage
- Power (through current measurement) (exported and imported)
- Power factor per phase
- Network frequency

Power (imported and exported) and power factor will be further used to predict energy consumption and generation by the EF, and voltages will be used to analyse the status of the grid and forecast possible critical events. Table 7 summarises the specifications of SM and GM data used in RESOLVD.

Table 7. SM and GM measurements specifications

Variable	Sampling period	Resolution	Potential receiver	Sending procedure to receiver
Power (exported and imported)	≤ 1 hour (Typically 15min or 1h)	$< 0.1Wh$	MDMS/ DMS (EF)	DCU pulls data every hour and it sends to the MDMS through the MDC.
Power factor		$< 0.1\%$		
Voltage		$< 0.1\%$	MDMS/ DMS (CEF)	

Besides, these devices provide information about the electrical load profile and power quality measurements by recording voltage variations outside the defined range and long-term interruptions of voltage.

4.2.4.PED

PED, as introduced in D2.1[12], is a device capable of acting on the grid by importing or exporting energy from/to a storage element (battery). Additionally, PED also incorporates sensors that measure a set of electrical variables.

Two main modules or layers composing the PED are: (i) the power layer, which includes the devices exchanging power with the grid; and (ii) the management layer, which includes the devices controlling the PED and communicating it with the rest of the grid. Figure 4 depicts PED architecture and locates PED measurements within it. According to it, PED's interface with other RESOLVD systems is the Intelligent Local Energy Manager (ILEM).

[12] Public deliverables will be accessible in https://resolvd.eu/documents/

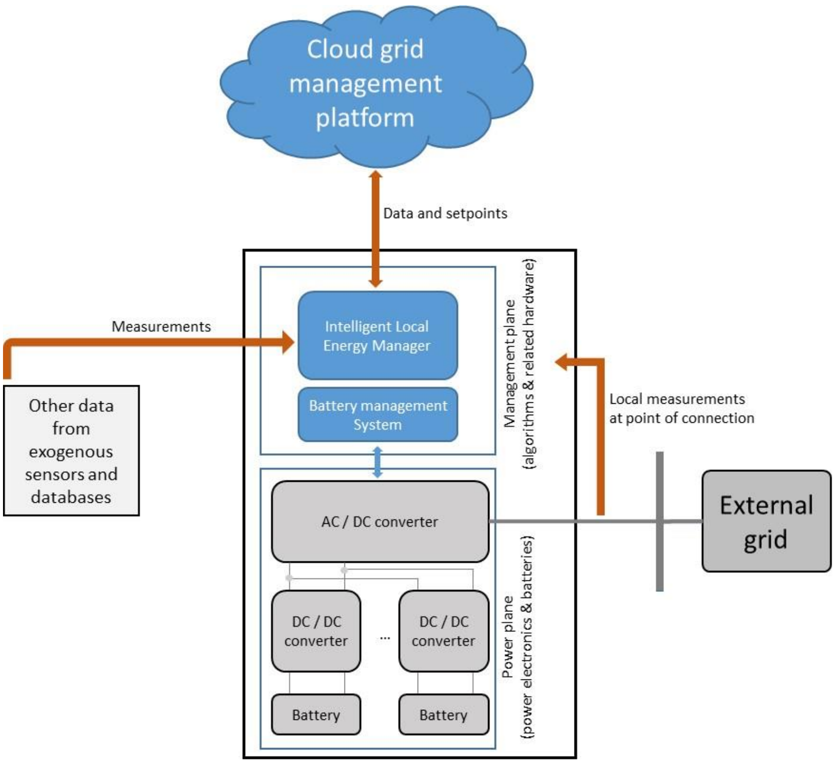

Figure 4. PED architecture

The PED is connected in shunt configuration with the grid. When connected to a Secondary Substation (SS), it will be connected to the LV side of the transformer. The net power exchanged by the transformer will not flow through the PED, but it will modify it by importing or exporting active and reactive power as needed. Figure 5 illustrates how PED is interconnected.

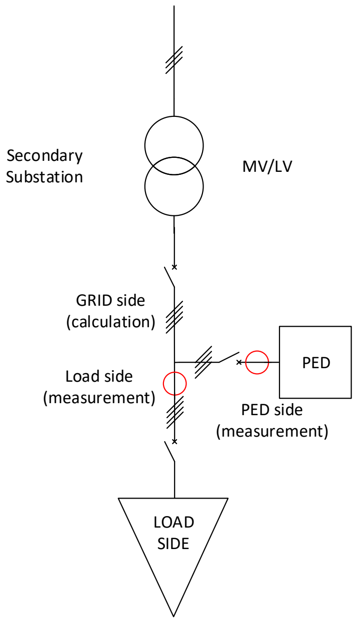

Figure 5 PED interconnection

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At the point of connection, the ILEM part of PED processes the following measurements, which can be exchanged with other systems:

- Active power
- Reactive power
- Voltage
- Battery status

Table 8 details the specifications of such measurements.

Table 8. PED measurements specifications

Variable	Sampling period	Resolution	Potential receiver	Sending procedure to receiver
3-phase active power	$\leq 1min$	$< 1\%$	SCADA	On SCADA's request, meaning that the ILEM is the server and the SCADA the client.
3-phase reactive power	$\leq 1min$	$< 1\%$	SCADA	On SCADA's request
3-phase voltage	$\leq 1min$	$< 1\%$	SCADA	On SCADA's request
Whole battery status (by BMS)	$\leq 1min$	$< 1\%$	SCADA	On SCADA's request
Harmonics	$\leq 1s$	-	PED (ILEM)	Estimated through a digital signal processing in the PED sampling at 30kHz. Estimation of harmonics at 150Hz, 250Hz, 350Hz, 450Hz, 550Hz, 650Hz.

4.3. Overview of the monitored variables

Table 9 summarises the devices used to monitor the LV grid and indicates (i) the variables available by each one, (ii) the associated data management subsystem (storage), (iii) the components that have access to these data, and (iv) the final purpose within RESOLVD.

According to it, observability requirements of HLUC01, HLUC04 and HLUC06 are met with the active and reactive power measured by SMs and GMs. These, data will be used by the EF to perform energy forecasts. These data can be accessed by the NTLFDA to find out if there is fraud in energy consumption as required by HLUC08.

HLUC03 aims at improving power quality. For this purpose, PEDs measure active and reactive power, and harmonics. These data are used by PEDs themselves for balancing currents between phases, correcting harmonics and controlling reactive power.

PMU data are used by the FDA as specified by HLUC05 for detecting, diagnosing and locating faults in the grid.

Finally, PED voltage measurements are used by the PED itself to detect the unplanned islanding of part of the grid and then, try to interrupt such islanding.

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Table 9. Metering and storage systems of the monitored variables, list of applications with access to the data and the final use of the monitored variables by RESOLVD applications

Physical variable	Instrument/ Metering device	Data handling subsystem	Actor consuming this data	Final purpose
3-phase voltage (RMS)	PMU	WAMS	FDA	Fault detection and localisation (HLUC05)
	PED	SCADA (only reported values)	PED	Voltage control (HLUC02), island interruption (HLUC07)
	SM/GM	MDMS	CEF	Critical event forecasting (HLUC01)
3-phase angles	PMU	WAMS	FDA	Fault detection and localisation (HLUC05)
3-phase active power/energy	PED	SCADA	PED	Current balance between phases and reactive power control (HLUC03)
	SM/GM	MDMS	EF NTLFDA	Energy forecasting (HLUC01, 04, 06), fraud detection (HLUC08)
3-phase reactive power/energy	PED	SCADA	PED	Current balance between phases and reactive power control (HLUC03)
	SM/GM	MDMS	EF NTLFDA	Energy forecasting (HLUC01, 04, 06), fraud detection (HLUC08)
Harmonics	PED	-	PED	Harmonics compensation (HLUC03)

4.4. Integration and connectivity

An integrated system and its communication links are depicted in Figure 6. In principle, we can distinguish among the following three subsystems:

- The integrated WAMS, PMUs and PQM, which are interconnected via GWs.
- The integrated SCADA and PEDs, which are interconnected through RTUs and GW, as well as, allow for interaction with PMU via GW (i.e. for voltage control purposes).
- The legacy AMI, which integrates SM and GM measuring devices with MDMS data management via DCU and MDC.

Figure 6 represents the different subsystems according to the distribution of zones and domains in the SGAM framework.

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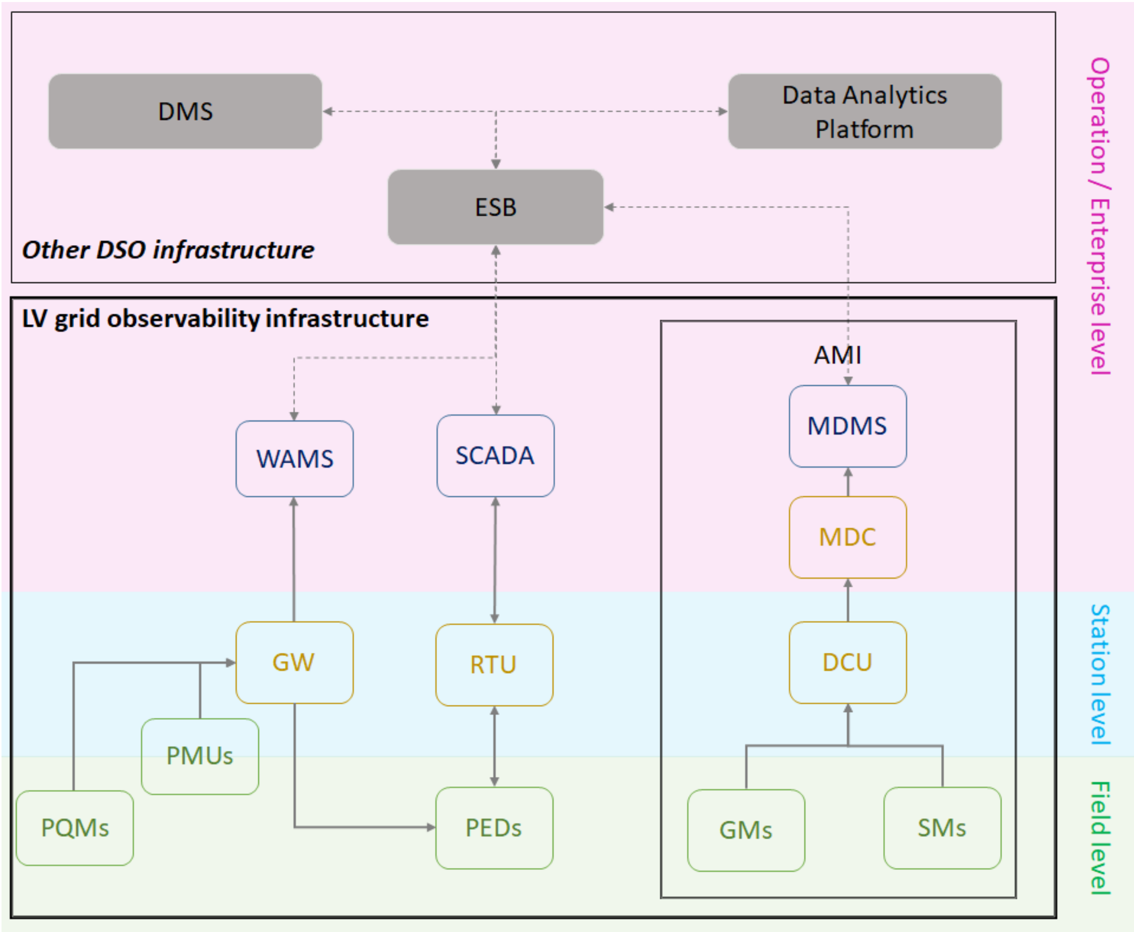

Figure 6. Connectivity among data sources and managers in the LVGOI

In general, LV grid observability data is managed and stored by three subsystems that have their own associated data bases: WAMS, SCADA and MDMS. The WAMS manages and stores data from PQMs and PMUs, SCADA manages and stores data from PEDs and switchgears among others, and MDMS manages and stores data from SMs and GMs. These systems are connected to the DMS and other RESOLVD applications through an Enterprise Service Bus (ESB).

Data from PMUs and PQMs are either aggregated at GW or send directly to WAMS server. The communication can either use dedicated wired (Ethernet, where available) or wireless cellular infrastructure.

Data from smart meters are concentrated through PLC to a DCU, which is placed at each SS level (MV/LV transformer) and then transmitted through the ICT infrastructure.

PEDs and SCADA use a different and separated infrastructure. In this case, sensors distributed on the grid, transmit data to the RTU, which is placed at each primary substation and in some SS. RTUs forward data to the central receiver, where it is transmitted to the SCADA.

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5. Conclusions

Project RESOLVD has the goal of increasing the hosting capacity of low voltage grids by increasing the flexibility of these grids. However, the exploitation of flexibility (changes in the generation and consumption values or changes in the grid configuration) require an accurate knowledge of the status of the grid. Therefore, RESOLVD also aims at developing a low voltage grid observability infrastructure in order to enable the continuous acquisition of information about the grid.

This document presents the specifications of the design of the aforementioned low voltage observability infrastructure and their subsystems. Thus, the document describes the specifications of the data to be acquired by this infrastructure and relates it to the needs identified in the description of the use cases provided by deliverable D1.1. Moreover, this document describes how the subsystems of this infrastructure are integrated together.

Since future smart grids require an increased quantity of information exchange and an increased level of automation, they also require to be robust and resilient against cybersecurity threats. Therefore, this document also provides an analysis of cybersecurity threats that can affect the whole infrastructure and its subsystems. This analysis will be extended in deliverable D1.4.

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