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e-balance

Deliverable D3.1

High Level System Architecture Specification

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Abstract

This deliverable specifies the high level architecture of the e-balance system. It provides a high level description of the components and the interactions between these components. The e-balance system consists of a hierarchical structure of energy management units, which naturally maps onto the grid infrastructure.

This high level definition of the communication and energy management platforms will be used as input for the work packages WP4 and WP5, respectively.

The proposed architecture will be refined in task T3.2 that will provide the detailed technical specification of the e-balance system.

Disclaimer

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Executive Summary

This document gives a high level description of the e-balance system and its functionality. The e-balance energy management system has a hierarchical structure, similar to the hierarchical grid infrastructure. This hierarchical structure will be used to efficiently perform the energy balancing and grid controlling tasks.

The high level architecture will be further specified within deliverable D3.2. The system specifications will then be used to design and implement the energy management system and the necessary communication platform in the work packages WP5 and WP4, respectively.

The structure of the document is as follows. In Section 2, the system architecture within the grid is presented. This section shows the hierarchical structure of the energy management units within the grid, and gives the generic architecture of these management units.

Section 3 presents the high level aspects of the communication platform. An overview is given on the network architecture, the middleware and the relevant security and privacy mechanisms.

Section 4 describes the main functionality of the e-balance system. The system balances the production, distributed and central, with the demand and supports the grid control.

Section 5 shortly describes the information flows within the system that are necessary to perform its tasks.

Finally, in Section 6, the document is summarized and an outlook to the tasks building on the architecture is given.

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Abbreviations

ADR	Automatic Demand Response
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CHP	Combined Heat and Power
CMS	Central Management System
CMU	Customer Management Unit
DAN	Device Area Network
DER	Distributed Energy Resources
DERMU	DER Management Units
DG	Distributed Generation
DMS	Distribution Management System
DMU	Device Management Unit
DSO	Distribution System Operator
ebEMS	e-balance Energy Management System
EMS	Energy Management System
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FAN	Field Area Network
FDLIR	Fault Detection, Location, Isolation and Restauration
GUI	Graphical User Interface
GPS	Global Positioning System
GW	Gateway
HAN	Home Area Network
HV	High Voltage
ICT	Information and Communication Technology
KPI	Key Performance Indicator
LAN	Local Area Network
LV	Low Voltage
LV-FAN	Low Voltage Field Area Network
LVGMU	LV Grid Management Unit
MDM	Metering and energy Data Management
MU	Management Unit
MV	Medium Voltage
MV-FAN	Medium Voltage Field Area Network
MVGMU	MV Grid Management
PS	Primary Substation
PS-LAN	Primary Substation Local Area Network
QoS	Quality of Service
S&A	Sensors and Actuators
SCADA	Supervisory Control And Data Acquisition
SGAM	Smart Grid Architecture Model
SS	Secondary Substation
SS-LAN	Secondary Substation Local Area Network
TLGMU	Top Level Grid Management Unit
TSO	Transmission Service Operator
WAN	Wide Area Network

1 Introduction

The main objective of the e-balance project is to design a smart and robust energy management system for the future electricity grid. This document provides the first step in this design process. In this deliverable, we define the high-level functional architecture of the e-balance system. In addition, the interface between the two e-balance platforms, the communication platform and the energy management platform is also defined.

In Section 2 we start with the overall architecture of the e-balance system. Like in the electricity grid, the management infrastructure of the e-balance system is set up in a hierarchical fashion. This is done to ensure scalability of the management algorithms. The hierarchical system results in several levels of management units. Although these management units operate in different levels in the grid, their architecture is similar. The high level management unit architecture is given at the end of this section.

Section 3 describes the communication platform. This includes a high level description of the communication network, the main middleware aspects and security and privacy mechanisms.

In Section 4 we focus on the energy management functionality. The system has two main functions: energy balancing (Section 4.1) and grid control and monitoring (Section 4.2). In Section 5, we give an overview of the information flows that are needed to provide the required system functionalities and that occur between the units in the system. Finally, we end with a summary in Section 6.

1.1 Deliverable Position in the Project

Figure 1 shows the position of this deliverable within the e-balance project. This deliverable is part of work package WP3 - System Specification. The specification is based on the results obtained in work package WP2 - Use cases and socio economic aspects. Especially, the use cases defined in deliverable D2.1 and the users and stakeholders requirements, defined in deliverable D2.4, are used to define the functional specification. Within this document, references are made to the key requirements stated in deliverable D2.4. Not all the requirements listed in deliverable D2.4 are referred to here, since there is much overlap between several of the requirements and some requirements are on a too detailed level for this high level specification. The requirements are referenced in the following form (Req. xx.y), where the identifier *xx.y* stands for the requirement identifier as defined within the deliverable D2.4. The legal issues defined in the deliverable D2.4 are referenced here as well. The legal issues that influence the functionality of the system are referenced as follows (Lxx.y), where *xx.y* stands for the legal issue identifier as defined within deliverable D2.4.

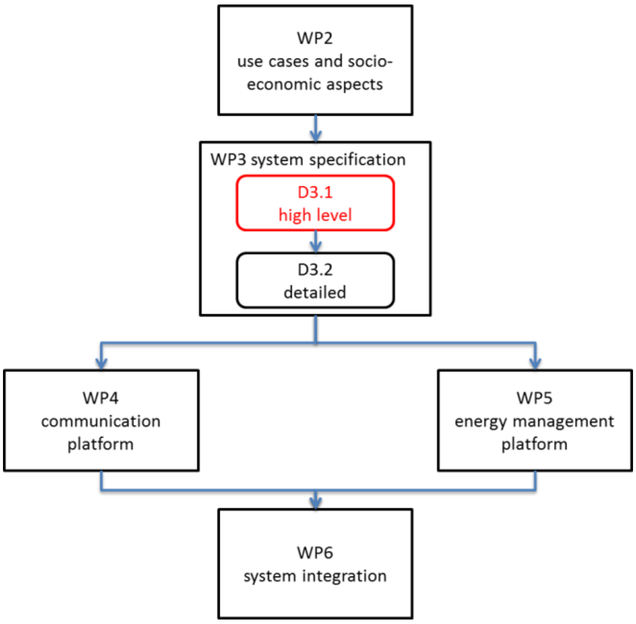

Figure 1: The position of the deliverable D3.1 within the e-balance project

The high level specifications given here will be refined in deliverable D3.2, which will result in the detailed system architecture specification. The architecture will provide the guidelines for the work in the work packages WP4 and WP5, in which the communication platform and energy management platform, respectively, will be developed.

2 System architecture

2.1 CEN-CENELEC-ETSI SGAM

The CEN-CENELEC-ETSI Smart Grid Coordination Group defined in late 2012 the Smart Grid Architecture Model (SGAM) framework [1]. The SGAM represents the smart grid domain in an abstract manner, and supports a large variety of approaches.

The SGAM framework spans into three dimensions, as shown in Figure 2:

- The SGAM framework identifies five Grid Domains
- The SGAM model comprises five Interoperability Layers
- The SGAM model identifies six Management Zones

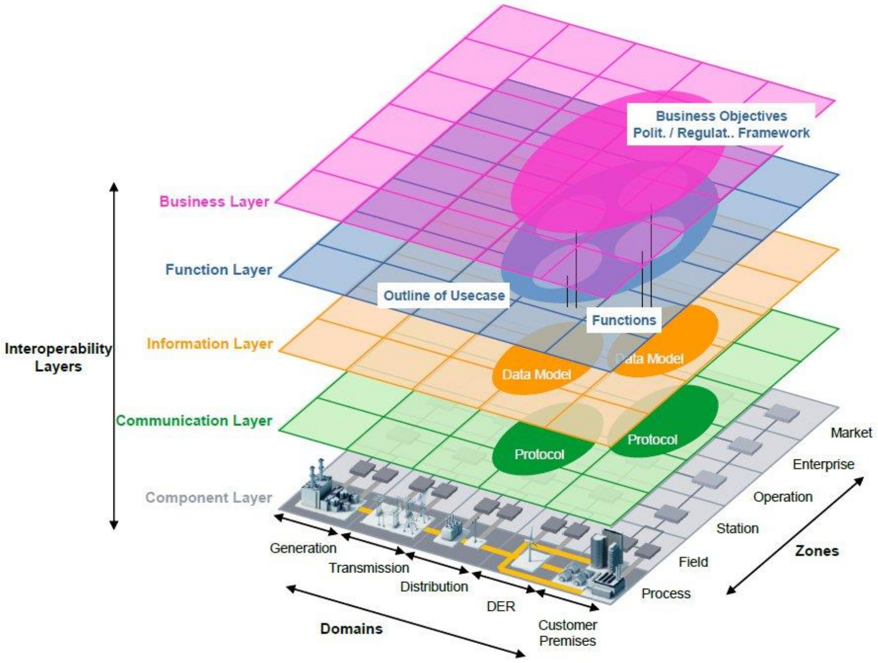

Figure 2: The SGAM framework

The SGAM framework identifies five Grid Domains, which are from left to right:

- Bulk Generation

  It represents the generation of electrical energy in bulk quantities, such as by fossil, nuclear and hydro power plants, off-shore wind farms and large scale solar power plants, typically connected to the transmission system. This domain is out of the scope of the e-balance project.

- Transmission

  It represents the infrastructure and organization, which transports electricity over long distances. This domain is also out of the scope of the e-balance project.

- Distribution

  It represents the infrastructure and organization, which distributes electricity to customers.

- Distributed Energy Resources (DER)

  It represents distributed electrical resources directly connected to the public distribution grid, applying small-scale power generation technologies.

- Customer Premises

  It represents the end users of electricity, who can also be producers of electricity. The premises include industrial, commercial and home facilities, e.g., chemical plants, airports, harbours, shopping centres, homes. It also includes distributed generation, e.g., photovoltaic generation, electric vehicles storage, batteries, micro turbines.

The SGAM model comprises five Interoperability Layers, which are from top to bottom:

- Business layer

  The business layer represents the business view on the information exchange related to smart grids.

- Function layer

  The function layer describes functions and services including their relationships from an architectural viewpoint.

- Information layer

  The information layer describes the information that is being used and exchanged between functions, services and components. It contains information objects and the underlying canonical data models.

- Communication layer

  The communication layer describes protocols and mechanisms for the exchange of information between components.

- Component layer

  The component layer describes the physical distribution of all participating components in the smart grid context. This includes system actors, applications, power system equipment (typically located at process and field level), protection and remote control devices, network infrastructure (wired / wireless communication connections, routers, switches, servers) and servers.

The SGAM model identifies six Management Zones, which are from top to bottom:

- Process

  It includes the transformations of energy (electricity, solar, heat, water, wind, etc.) and the physical equipment directly involved, e.g., generators, transformers, circuit breakers, overhead lines, cables, electrical loads and related sensors and actuators.

- Field

  It includes equipment to protect, control and monitor the process of the power system, e.g. protection relays, bay controller, any kind of intelligent electronic devices which acquire and use process data from the power system.

- Station

  It represents the aggregation level for field level, e.g. for data concentration, functional aggregation, substation automation, local SCADA systems, plant supervision.

- Operation

  It includes power system control operation in the respective domain, e.g. Distribution Management Systems (DMS), Energy Management Systems (EMS) in generation and transmission systems, microgrid management systems, virtual power plant management systems (aggregating several DER), electric vehicle (EV) and fleet charging management systems.

- Enterprise

  It includes commercial and organizational processes, services and infrastructures for enterprises (utilities, service providers, energy traders, etc.), e.g. asset management, logistics, work force management, staff training, customer relation management, billing and procurement.

- Market

  It represents the market operations possible along the energy conversion chain, e.g. energy trading, mass market, retail market.

The e-balance project spans a large part of the SGAM framework. Only with respect to the grid domains it is limited to the Distribution, DER and Customer premises domains. This leaves the Bulk Generation and Transmission domains out of scope.

2.2 E-balance System Architecture

This section describes the details of the e-balance high-level system architecture and explains how the system components are mapped onto the grid.

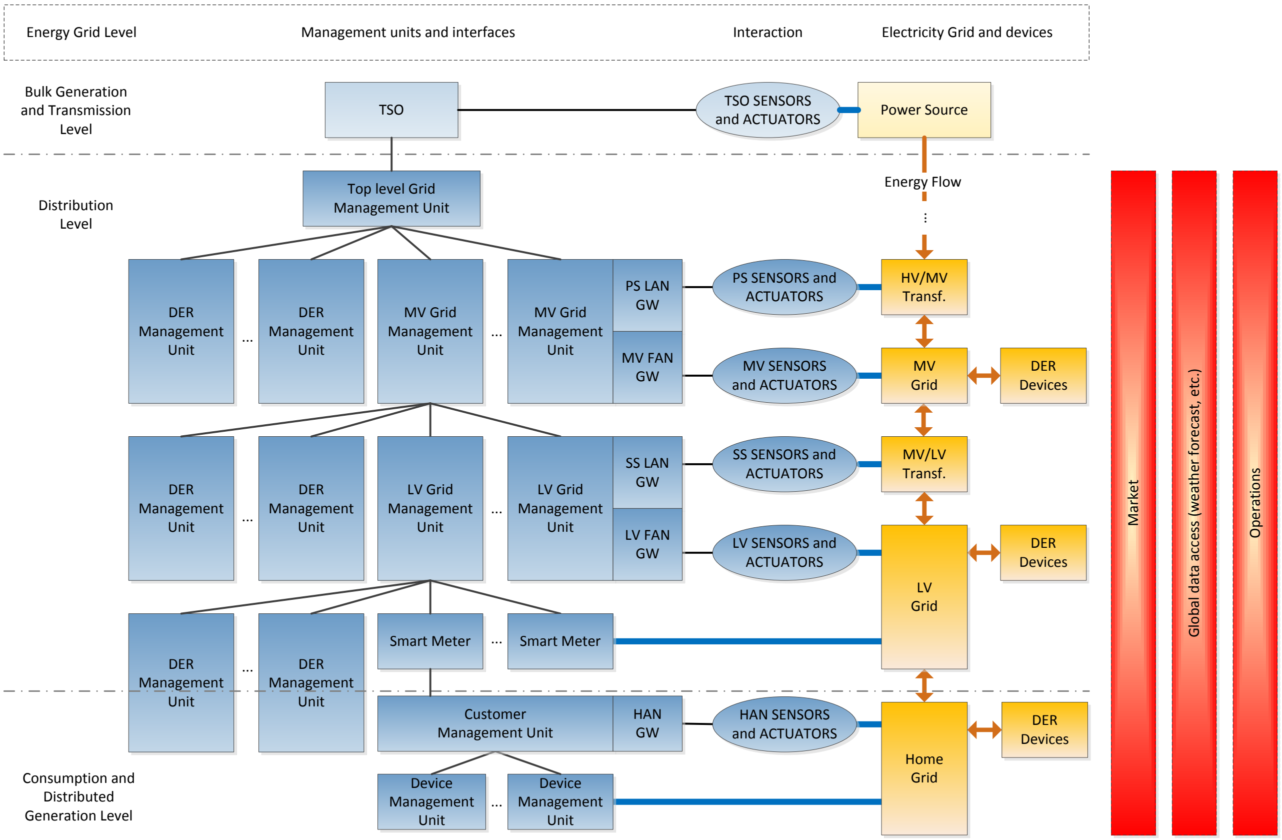

Figure 3: The e-balance high-level system architecture within the grid

The e-balance system architecture, shown in Figure 3, is compatible with SGAM, although it has been adapted to the objectives of e-balance by detailing the domains and components that are the focus of the project and omitting the others that are out of the scope of the project. For simplification of the representation, the three dimensional SGAM model was transformed into a two dimensional hierarchical model, easier to handle. The Energy Grid level corresponds to the SGAM domains, the Market, Global Data Access and Operations correspond to the SGAM zones and the SGAM interoperability layers are distributed among the e-balance system components and their interaction with the energy grid components. In the system architecture the bulk generation and transmission levels are collapsed as they are out of the scope of the project. We also subdivide the Distribution level into two segments: Medium Voltage (MV) and Low Voltage (LV).

For clarification, in the further text of this document we use the term grid to refer to the energy grid. In contrast, the term network is used to represent the communication network within the e-balance system.

The e-balance system architecture shows the system components and their interactions as well as their relations with the grid. In Figure 3, the e-balance system components are represented by dark blue coloured shapes. The light blue boxes represent the Bulk Generation and Transmission Level that is out of project's scope. The e-balance system involves several management units and the figure depicts the hierarchical tree of these management units with a single management unit level for each voltage level in the grid. In very dense networks intermediate management unit levels may be applied to reduce the data load in the network and to distribute the local decisions further.

The yellow coloured shapes represent the grid and the devices within the grid. Finally, the red coloured boxes represent virtual layers like the Market, Global Data Access and the Operations. The different lines in the figure represent different kinds of interaction between the modules they connect. Black lines represent the network, i.e., the data exchange that involves the management units, as well as the sensors and actuators. Blue lines represent the interaction between the e-balance system and the grid, i.e., the reading data from sensors located in the grid and control signals to trigger actions by actuators in the grid. Finally, the orange lines represent the flow of energy within the grid.

Figure 3 shows all the domains of the grid, i.e., the consumption and distributed generation level representing the customer premises, the distribution level representing the distribution grid, as well as the bulk generation and transmission level. However, as already mentioned the latter is out of scope of the e-balance project and is presented here only for the sake of clarity.

All the management units have a similar architecture, which is described in detail in Section 2.3. However, depending on the level, the management units may have different roles and duties. The processes executed on them may operate on behalf of different stakeholders and process data from different stakeholders. But, since at every level the concept of data collection and processing is similar and the e-balance system architecture is fractal-like, the management algorithms applied on different management levels share the same conceptual base, what improves the scalability of the approach.

The device level is the lowest level represented in the architecture. A device may be of any kind, including home appliance that only consumes energy, but it may also be an energy generation or storage unit. The device management unit is a central unit of the device that is aware of the current state of all the components that the device consists of and controls these components. The device management unit is also equipped with a communication module or gateway that allows upward communication with the higher level management unit, i.e., the Customer Management Unit (CMU) that controls all the customer devices at the customer premises.

The customer management unit is also equipped with several communication gateways. It communicates downwards with its underlying device management units, but it also communicates with Home Area Network (HAN) sensors and actuators that interact with the home grid providing grid monitoring and control, but also support the home automation functionality. The customer management unit is aware of the state of each device as well as of the individual and cumulative energy consumption and production figures. Thus, it can also provide the accounting functionality of a smart energy meter. However, in order to do this correctly the device has to be approved by the distribution system operator (DSO), thus in order to give some flexibility for the customers with respect to choice of the customer management unit, we introduced the smart meter as an additional (possibly virtual) layer in the architecture. We did this also in order to separate the customer and the distribution grid domains regarding the data and device ownership, as well as to identify and highlight the interface between these two domains. Identifying the single interface and the data passing thought this interface simplifies the task of privacy protection and the defining and enforcing the data handling settings. By doing that, we also defined the split in roles and in communication for these two (possibly separate) units, i.e., the smart meter and the customer management unit. This also allows several possible configurations within the customer premises. A stand-alone customer management unit may work as a home automation device, managing the customer devices, even if no smart meter is present. But if the latter is present, either as a separate device or as a built-in functionality, the customer management unit communicates with the outside world via the smart meter and controls the local consumption and production according to the context in the neighbourhood. Thus, the smart meter is a gateway for the customer management unit that connects it with the outside world and provides it with information from the grid. Further, the smart meter is a sensor itself, i.e., it measures at least the energy flow. So, as already mentioned, these two units may be a single device, but from both the customer, as well as the DSO's perspective the separation may simplify the acceptance, i.e., each stakeholder owns a device and can choose the exact device shall be used, e.g., if several are available on the market.

A Distributed Energy Resources (DER) management unit (DERMU) corresponds to the device management unit for some specific DER device that may be connected to different voltage level parts of the grid, i.e., the home grid, the LV grid or the MV grid. The customer may give some of the control over the DER devices at his premises to external stakeholders, like the DSO. Thus, in case of the home grid DER devices, the DER management unit may cross the border between the customer and the grid domain.

The level above the customer management units consists of low voltage grid management units (LVGMU). These management units are located at the secondary substations and each of them controls the sensors, actuators, customer management units and DER management units located in the area of the grid supplied with energy by this secondary substation. A LV grid management unit is equipped with communication gateways for the upward and downward communication within the e-balance management hierarchy. It is also equipped with communication gateways for communication with sensors and actuators located at the MV/LV transformer (Secondary Substation Local Area Network – SS-LAN) and also in the LV grid feeders related to the secondary substation (Low Voltage Field Area Network – LV-FAN). All these communication gateways may be different, depending on the technologies used in each part of the network.

A medium voltage (MV) grid management unit (MVGMU) is similar to its counterpart for the low voltage. A MV grid management unit resides at a primary substation. It is equipped with upward and downward communication gateways and controls all the sensors, actuators and LV management units located at secondary substations related to this primary substation as well as the DER management units in the area for DER devices connected directly to the LV grid (in contrast to those at customer premises). In order to interact with the sensors and actuators at the HV/MV transformer the MV grid management unit is equipped with Primary Substation Local Area Network (PS-LAN) gateway. Similar, for communicating with the sensors and actuators in the MV grid related to the primary substation the Medium Voltage Field Area Network (MV-FAN) gateway is available at the MV grid management unit. Again, the communication gateways may use different communication technologies.

The top level grid management unit (TLGMU) controls all MV management units as well as all the DER management units for DER connected directly to the MV grid, i.e., it collects all the status data and sends control signals to all the lower level management units. The top level grid management unit may be considered as a control centre that provides also interfaces for management tools, like supervisory control and data acquisition (SCADA), market management, outage management, Distribution Management System (DMS), and Metering and energy Data Management (MDM). The top level grid management system communicates also with the Transmission Service Operator (TSO).

At the bulk generation and transmission level, the TSO may also use sensors and actors to interact with the transmission grid and the generation that are defined as the Power Source in the figure.

The following section describes the management unit architecture and thus, further and in more detail explains the overall architecture.

2.3 Management Unit Architecture

An e-balance management unit can be regarded as a concentrator that controls all its directly subordinated elements, i.e., lower level management units, sensors and actuators, by taking control decisions based on the user configuration and interaction as well as the context received from the parent management unit and on the data obtained from these subordinated elements. In order to fulfil this task in a well-organized way, the core functionality of the management unit that interacts with the respective part of the *energy infrastructure* is split into two main blocks, i.e., the *communication platform* and the *energy management platform*. The former is responsible for the data gathering and exchange within the network, while the latter represents the logic on the unit that takes the local decisions based on the data. The general architecture of an e-balance management unit is presented in Figure 4.

The management unit communicates with sensors and actuators, which interact directly with the part of the grid the unit is responsible for, as already mentioned in the previous section. It also communicates with its subordinated management units that, in turn, represent some specific parts of the grid under their jurisdiction. Finally, each management unit, except the top level one, also communicates with its parent management unit. The top level management unit communicates with the TSO. All these mentioned different communications may use different communication technologies and thus, they may require different networking protocol stacks. Thus, in the unit architecture, as shown in Figure 4, there are several networking protocol stacks, one for the communication upwards the hierarchy, one for the communication downwards the hierarchy and several networking protocol stacks for the communication with sensors and actuators. This latter set represents the virtual *sensor interface* that covers all possible interfaces that allow accessing data from a sensor or controlling an actuator and is depicted in the figure between the communication platform and the energy infrastructure. The *sensor interface* is actually a *sensor and actuator interface*, but, for simplicity, it will be referred to as the *sensor interface*. Additional networking stack may be also required for the user interface device if it is implemented as a separate device that provides the graphical user interface (GUI).

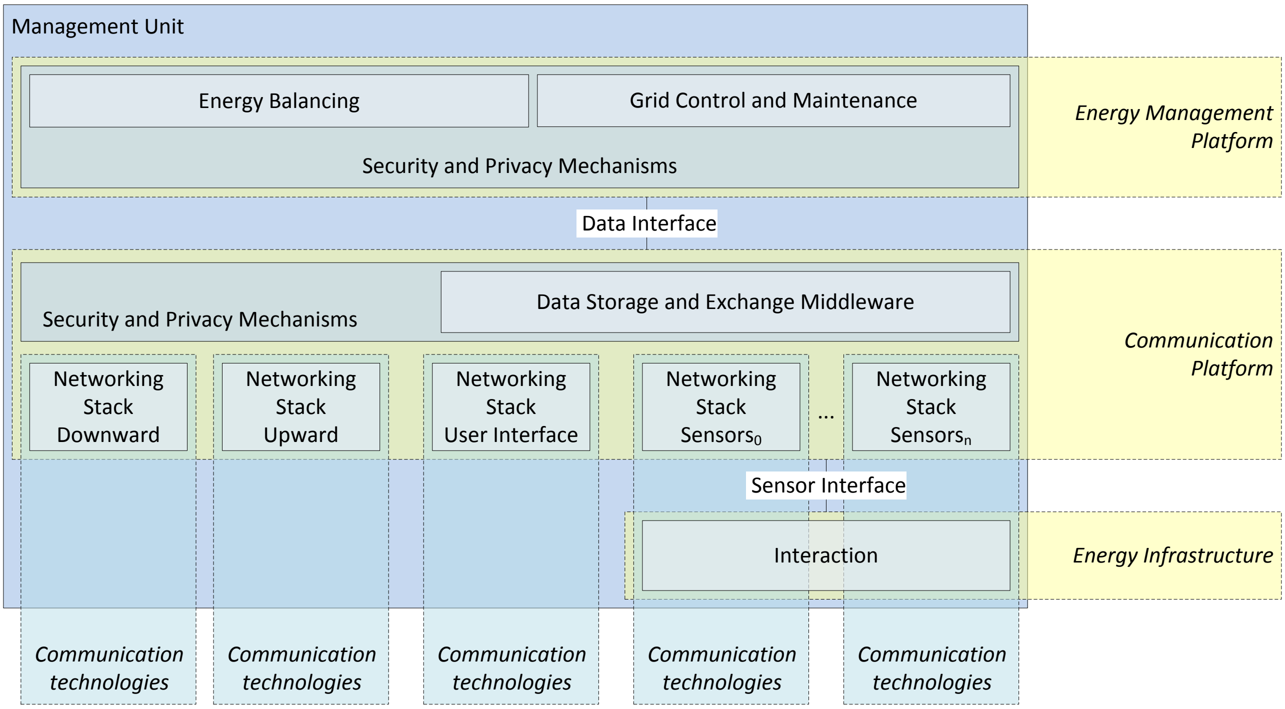

Figure 4: The general architecture of an e-balance management unit

The *data storage and exchange middleware* is placed on top of the networking stacks. Its aim is to provide the abstractions to simplify data addressing, data access and data exchange between different management units. The middleware is supported by the *security and privacy mechanisms* to protect the exchanged data. The middleware provides the *data interface* that connects the communication platform and the energy management platform. This interface shall be the only interface used by the energy management platform to access the data it uses for its operations.

As already mentioned the energy management platform is placed on top of the communication platform and it includes the logic modules that perform different kinds of operations based on the data provided by the communication platform and provide their results and control signals through the communication platform as well. These logic modules are supported by security and privacy mechanisms that operate at a higher level than their counterparts of the communication platform.

The energy management platform modules include the *energy balancing* module that provides the estimates for energy to be produced and consumed in the (near) future based on the historic consumption data but also on additional parameters, like the weather forecast data. This module compares the predicted values with actual situation and triggers actions on the devices and units under its control to keep its part of the grid in a stable state with respect to energy production and consumption. On the other hand, the *grid control and monitoring* module analyses the state of its part of the grid and generates control signals to control the grid quality of service. These two above mentioned modules are responsible for different aspects but they cooperate closely. They provide the status and summary to their counterparts on the parent management unit and generate control signals for the subordinated management units and actors in the part of the grid; their local management unit is responsible for. These control signals steer the actions necessary for energy balancing and management.

2.4 The Data Interface

The Data Interface that is provided by the data storage and exchange middleware defines the data exchange between the communication platform and the energy management platform. The exact implementation details of the interface will be defined in deliverable D3.2. In the following paragraphs we sketch the most important aspects of the abstract interface together with the way the data is represented and addressed.

The data interface is data centric and allows exchanging defined data elements (variables) between the two major parts of the system. The interface also provides access control for the data accesses. This means that the sources of the data access requests are identified and only allowed accesses are executed. The data access requests are generated by processes in the energy management platform that request data from the communication platform on behalf of some stakeholder. Thus, prior to the actual data access they have to identify themselves as well as the stakeholder they work for. The access to the data is granted or denied according to the data specific access strategy (privacy policy definitions) specified by the data owner (data source). The data owner may specify individual access strategy for each data item (variable) separately. This definition is stored and transmitted together with the data structure containing the value of the variable. This approach allows checking and enforcing the access policy without the need to obtain this policy from the data source. Additionally, it allows changing the access policy without affecting the data that was generated prior to the policy change.

The data structure containing the variable stores also the meta-data that is used to address the data in the middleware. This meta-data provides a multidimensional address space allowing identify the data in temporal and spatial domain.

Thus, to summarize, the data structure contains the following items:

- Identifier of the variable, e.g., current, voltage, temperature, wind direction, solar radiation, etc.,
- Value of the instance of the variable,
- Temporal identification of the instance, e.g., a timestamp or a version number,
- Spatial identification of the instance, e.g., geo-coordinates, location in the hierarchy,
- Identifier of the instance owner,
- The privacy policy defined by the data owner.

The Data Interface operates on the data structures and allows executing the following requests/operations:

- Reading,
- Writing,
- Subscribing,
- Unsubscribing.

These requests are executed or rejected based on the policy defined by the data owner. The access policy check is realized for each data item to be delivered, allowing for instance to limit the frequency the values of a variable may be received by some specific stakeholder or by all stakeholders.

2.5 The System Architecture Examples

We can use the customer management unit, the lowest level in the e-balance system architecture to give an example that explains the above mentioned relations and communication between management units on this level of the proposed system architecture.

The aim of the customer management unit is to control the customer appliances according to the user settings and interaction and according to the control signals obtained from outside the customer premises, i.e., from the neighbourhood or, in general, from the grid. The appliances are controlled with respect to both energy consumption and energy production.

Figure 5 shows an example set-up within customer premises involving the e-balance system components. The colours of the shapes and lines correspond to the colour scheme in Figure 3, i.e., blue shapes represent the ICT infrastructure, yellow shapes represent grid devices, orange lines represent energy flows and the black lines represent data/control flows. This example set-up involves four smart appliances and each of them is equipped with a device management unit. Additionally, there are power sensors (watt meters) and actuators (switches) available, e.g., they can belong to the home automation system. Further, from the distribution grid side, individual smart meters are applied for measuring the customer consumption and production of energy. Thus, the home grid is physically split into two parts, one for locally produced energy and the other for the consumed energy. The physical separation of these two parts of the grid can already be less attractive to the customer. Additionally, in case of a market where the customer sells the produced energy for much less than he pays for the consumed units this set-up represents the extreme and less attractive case for the customer. In the example set-up, the energy production is controlled directly by the customer management unit, thus there are no additional DER management units applied for the devices producing energy.

As already mentioned, in this set-up all the produced energy is brought to the grid and thus, it is, for instance, not possible to consume it locally or to charge the local energy storage directly using the energy produced by the solar panels. All the produced energy has to leave the customer premises first to be accounted on the meter for produced energy and then may go back over the meter for consumed energy. This scenario shows the Portuguese situation where separate smart meters for consumption and production are required. This meter configuration is actually not optimal from the customer point of view, but we can use it in the first step of the explanation of the e-balance architecture as it expresses the first stage of the smart grid deployment, where not many appliances are smart and thus, additional external watt meters and switches are required in the home grid to enable controlling standard appliances.

This set-up is redundant due to the fact that there are two smart meters and by the fact that the intelligent devices are also controlled by additional external sensors—power meters and actuators—switches. This functionality—measuring the consumption or production as well as disconnecting the device from the grid—may be already provided by the intelligent appliances, but the additional energy measuring sensors and actuators can be part of the home automation system and may be also used to improve resilience within the home grid, i.e., the malfunctioning appliances can be disconnected from the home grid.

In this first example set-up the two smart meters measure separately the total customer production and consumption and they provide this information to the grid (to the low voltage grid management unit) for processing that results in control signals for the individual customers. Each of the smart meters provides the customer management unit with control signals and data from the grid related to the respective energy flow direction. For instance, if the grid needs more energy due to higher demand, the production smart meter propagates the request to the customer management unit asking for increasing the production. On the other hand, in the same case, the consumption smart meter propagates the request asking for reducing the consumption. Similar, the energy prices for consumed and produced energy are propagated to the customer management unit via the respective smart meter.

Thus, the customer management unit is a control unit that monitors the appliances' energy consumption and production using sensors (stand-alone or integrated in smart appliances) and controls these smart appliances and actuators (e.g., switches) based on the influence of the user interactions and on the set of input data. This input data includes the user preferences and strategies in a rather static way and the dynamic data like the actual appliance usage as well as control signals and data from the grid and the sensor readings from the home grid that monitor the appliances operations, but also other phenomena, like user presence, etc.

In order to achieve its tasks in the home area, the customer management unit exchanges the data with the power sensors, switch actuators and the device management units. The power sensors are used to monitor the energy flow, to detect overcurrent and may also be used to verify the devices' power consumption and production data provided by the device management units, if they provide this kind of information. The customer management unit does not have to be aware of the internal processes executed on the device level, like the device-specific schedule for the energy consumption. These details are abstracted and managed by the device management units—the device built-in module with its local intelligence defined and implemented by the appliance vendor. Thus, all the device components within the device are in the responsibility of the device management unit that provides only the most important data to its parent—the customer management unit. Depending on the applied level of smartness, the smart appliance's device management unit provides different information and control over a defined smart appliance data interface.

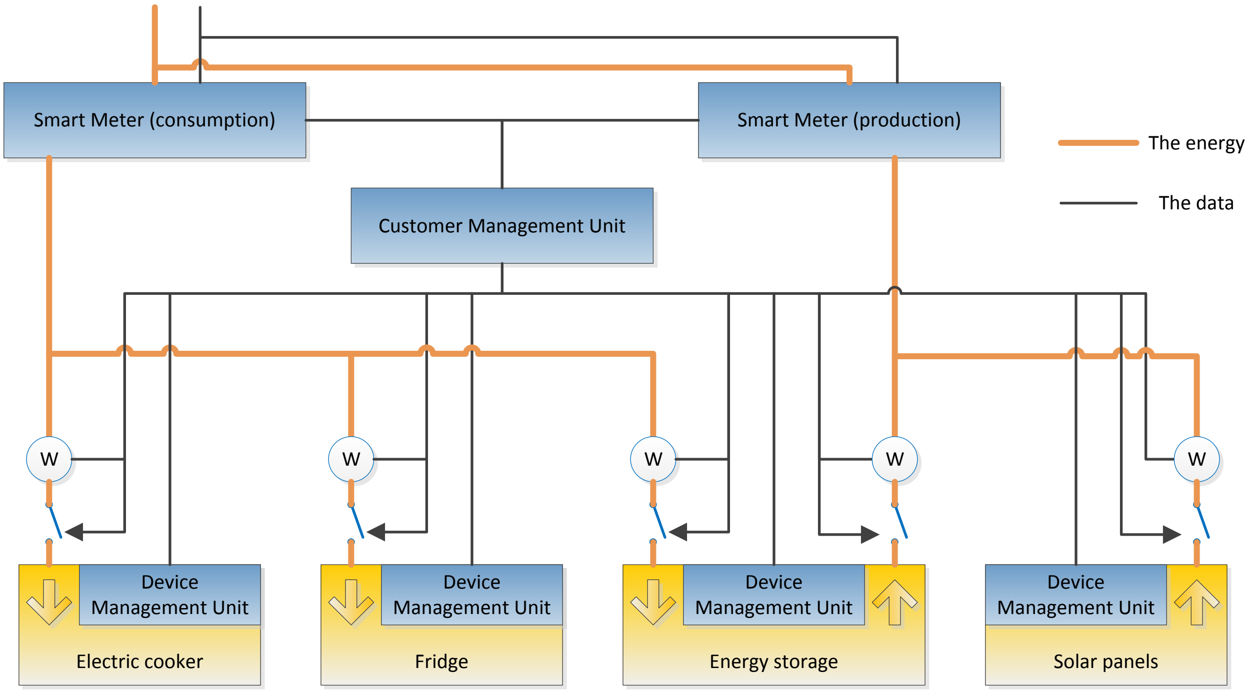

Figure 5: Customer management unit example set-up

To give an example of the management unit interaction we can consider a dynamic case for the energy balancing. Let us assume that the low voltage grid management unit (on the hierarchy level above the smart meters) generates for each customer a proposal on the levels of the produced energy and the consumed energy for a given time period, e.g., next 15 minutes. These values are communicated to the respective smart meters and are then propagated to the customer management unit. The customer management unit computes a prognosis for the next 15 minutes using the prediction mechanism. If the prognosis differs from the received proposal, the customer management unit replies with the updated value either for production, or consumption or for both via the respective smart meter. The smart meter propagates the numbers to the low voltage management unit. This negotiation process may be repeated until they will find a consensus.

After defining the amount of energy to be consumed and produced within the given time period, the customer management unit monitors the current energy consumption figures using the watt sensors (either built-in in the devices or external) and compares them with the plan. If unexpected changes in the energy consumption occur, the customer management unit adapts to that event. For instance, if the customer unexpectedly decides to use all four heating plates of the electric cooker, then the demand rises dramatically. In this case the customer management unit tries to reduce the consumption of other devices to achieve the plan, e.g., it stops the charging of the energy storage, stops the freezing in the smart fridge and additionally reduces the power of each of the heating plates in the cooker. If achieving of the plan is in danger, then the customer management unit computes the costs or consequences of that situation and either decides to take the consequences and, e.g., to pay more for the extra energy, to intervene to achieve the plan or it may try to break the agreement as little as possible, e.g., by switching off two of the heating plates.

In the opposite case, where the actually consumed energy is smaller than the plan, the customer management unit may decide to store the energy in the energy storage or to take the consequences, e.g., to pay for the not used, but ordered energy.

In the both cases, where the plan differs from the actual energy consumption, the customer management unit also notifies the respective smart meter and the low voltage grid management unit about the fact and may order additional energy or offer the not used energy to the grid.

The customer management unit monitors also the amount of energy produced by the solar panels. Comparing the actual production with the plan the customer management unit can control the storage to release the energy stored in the storage (if available) to cover the gaps in the production plan. If the production is higher than expected, the additional energy may be offered to the grid. Then the customer management unit informs the low voltage grid management unit about the additional energy.

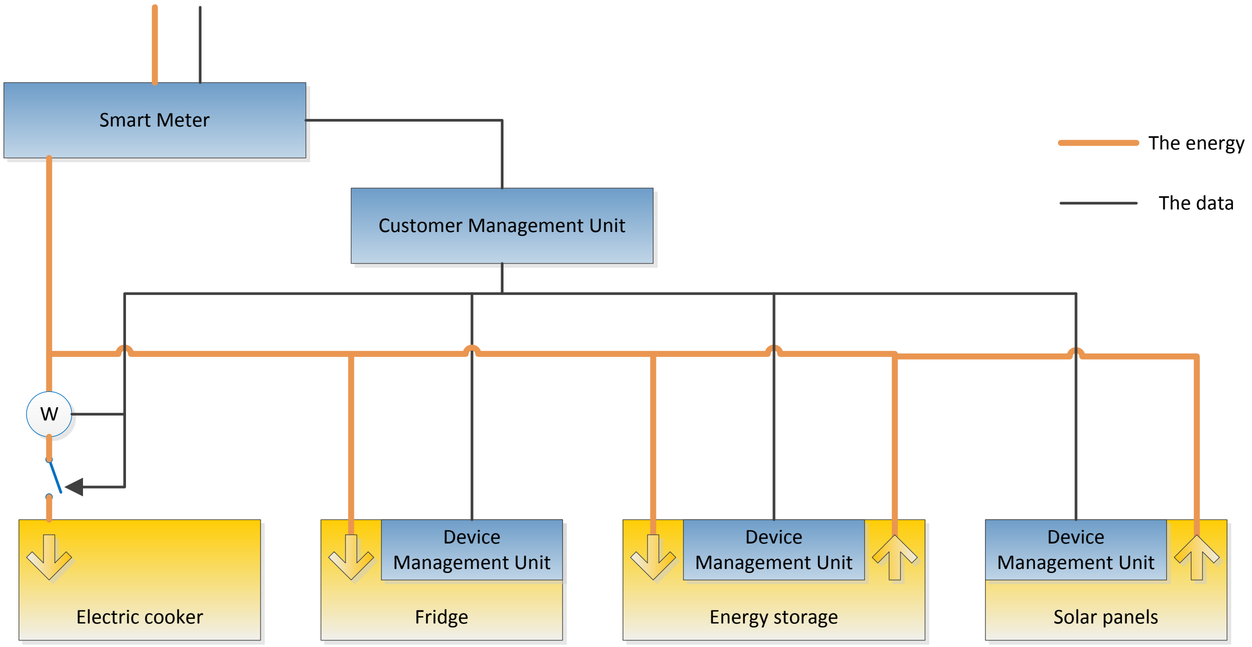

Figure 6: The improved customer management unit example set-up

The second set-up presented in Figure 6 assumes that the smart appliances are smart-grid-capable and thus, no further sensing nor actuators are needed to provide all the necessary functionality, i.e., measuring the actual energy consumption and production as well as controlling the connection to the grid is realized by the device internally and is controlled by its device management unit. In turn, the customer management unit controls these smart appliances directly and only for standard appliances the external sensors measuring the consumption and actuators allowing disconnecting the appliance are necessary (see the electric cooker in Figure 6).

Additionally, this second example set-up uses only one smart meter to measure both, the consumed energy and the produced energy, e.g., as a sum. Due to that all the appliances are connected to the same home grid, allowing for more flexibility in managing the energy, since the produced energy can be used and stored locally.

We show that increase of flexibility taking again the example scenario, where the low voltage grid management unit and the customer management unit agree on the amount of energy to be consumed and produces at the customer premises. Even if the smart meter is equipped with separate counters for outgoing and ingoing energy the home internal management and balancing in the second set-up is easier, because as long as there is consumption and production happening at the same time, these two agreed numbers become de facto a sum and it is important that this sum corresponds to the numbers from the agreement. Of course such assumptions depend on the local regulations and market rules.

Thus, after defining the amount of energy to be consumed and produced within the given time period, the customer management unit monitors the current energy consumption and production figures using the built-in power sensors for smart appliances and the external power sensor for the electric cooker and compares them with the plan. If unexpected changes in the energy consumption or production occur, the customer management unit adapts to that event. And again, if the customer unexpectedly decides to use all four heating plates of the electric cooker, then the demand rises dramatically. And in the second set-up, in this case the customer management unit tries to reduce the consumption of other devices to achieve the plan, e.g., it stops the charging of the energy storage and stops the freezing in the smart fridge. In this set-up it cannot control the power of the individual heating plates in the cooker, since this appliance is not smart. But it may also involve the local energy production to fill the energy gap, increasing the power produced by the solar panels and/or discharging the energy storage, if there is energy available. But of course, if achieving of the plan is anyway in danger, then the customer management unit computes the costs or consequences of that situation and either decides to take the consequences and pay more for the extra energy or to intervene to achieve the plan or to break the agreement as little as possible. The worst case intervention is to switch the electric cooker off completely using the external switch actuator. The decisions of the customer management unit are of course driven by the strategy defined by the customer.

In the opposite case, where the actually consumed energy is smaller than the plan, the customer management unit may still decide to store the energy in the energy storage or to take the consequences and, e.g., to pay for the not used, but ordered energy, if the storage is already full. On option could also be to reduce own production to keep the sum as agreed. On the other hand, in case the actual energy production is smaller than the agreed amount, the customer management unit may also reduce the customer energy consumption to keep the sum as agreed.

3 Communication Platform

The communication platform will be completely defined and developed in WP4. Here we present the communication platform aspects related to the high-level system architecture. In Section 3.1, the network architecture is introduced, in Section 3.2, the same is done for the middleware and, finally, in Section 3.3, we introduce the relevant security and privacy mechanisms for the communication platform.

3.1 Network Architecture

The aim of the e-balance networking protocol stacks is to provide communication mechanisms. These shall allow the individual management units to communicate with each other as well as to allow communication between management units and sensors/actuators or GUI devices.

The e-balance communication network architecture for the energy distribution is of course compatible with the e-balance system architecture (see Figure 3) and is depicted in Figure 7.

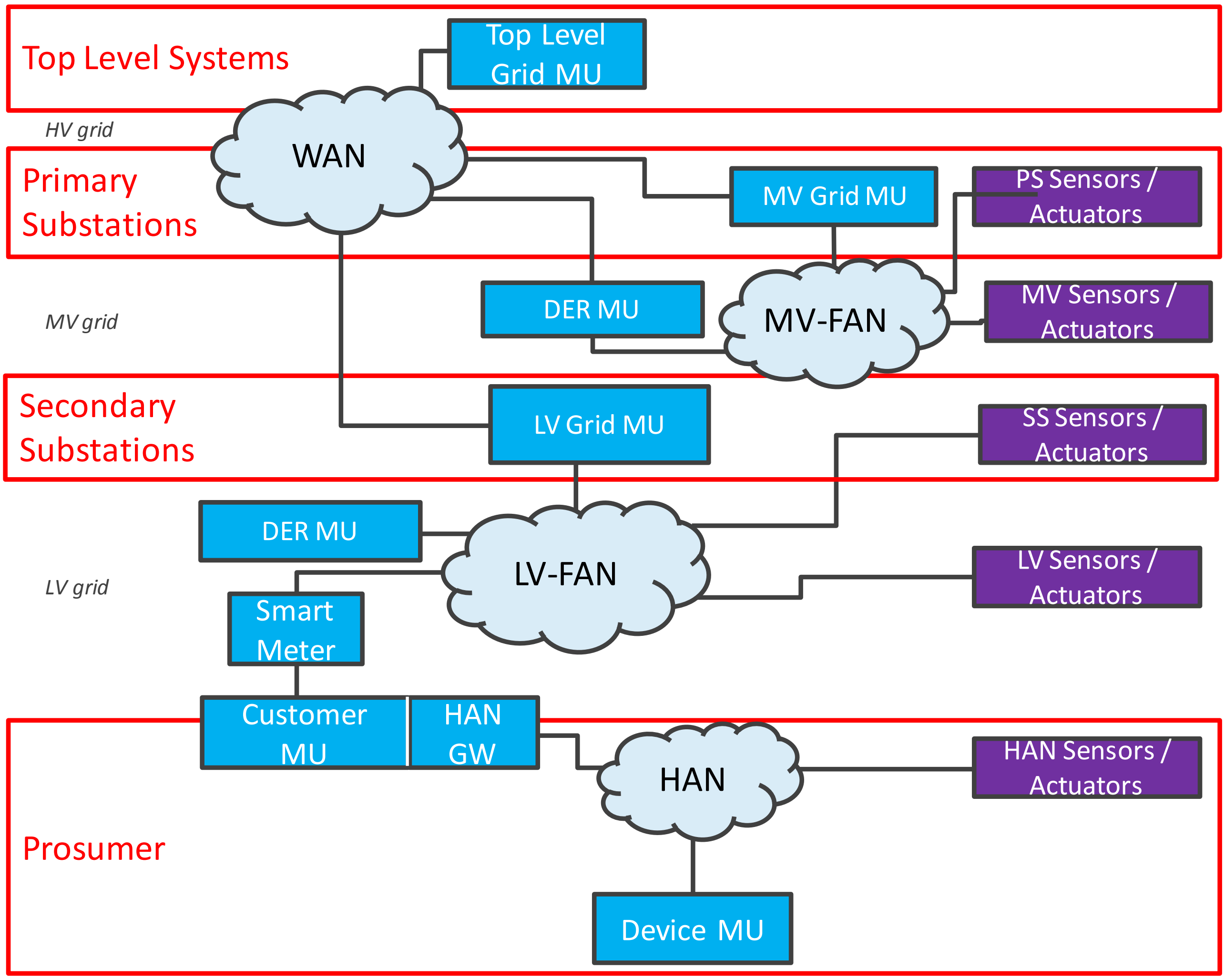

Figure 7: The e-balance communication network architecture.

The communication architecture is structured in four levels. The top level corresponds to the Central Management Systems (CMSs), where the top level grid management unit resides. This forms the core of the Smart Grid distribution intelligence and must be fed by data coming from the systems and devices that lie below in the network architecture, while issuing management and control commands downstream.

The next level is constituted by the Primary Substations (PS), each comprising an MV grid management unit. The latter gathers data from sensors located within the PS, as well as from MV field sensors, issuing management and control commands to MV grid actuators. It also interacts with DER MUs as well as with

LV grid management units located at the Secondary Substations. Communication between the top level grid management unit, the MV grid management units and LV grid management units is accomplished through a Wide Area Network (WAN) technology due to the large geographical scale associated with the regional character of distribution at the top levels of the grid architecture. Communication between the MV grid management unit, MV field sensors/actuators and DER MUs is accomplished through the MV Field Area Network (MV-FAN). The character of the MV-FAN is more local since the sensor/actuator nodes are located in devices and/or power lines that constitute a grid subset that is directly connected to the Primary Substation.

The level below is constituted by the Secondary Substations (SS), which are responsible for low voltage energy distribution at a neighbourhood scale. Each SS comprises an LV grid management unit, which receives data from LV sensors as well as from the Smart Meters and DERs located in the LV, issuing management and control commands downstream (e.g., control of LV actuators, load management and control of DERs located in the LV). Connectivity between the LV grid management unit, Smart Meters, LV field sensors/actuators and DER MUs is accomplished through the LV-FAN.

Finally, we reach the bottom level constituted by the prosumer premises. The Smart Meter is able to control advanced power consumptions functionalities and it also manages the power outputs of energy generating devices based on the set points issued by the LV grid management unit. The Smart Meter is directly connected to the customer management unit. Connectivity between the customer management unit, appliance sensors, actuators and device management units is accomplished through the Home Area Network (HAN).

In summary, the e-balance communication network architecture comprises four network areas: WAN, MV-FAN, LV-FAN and HAN. These network areas will instantiate the communication needs of the information flows between the different entities represented in the system architecture. These information flows will be identified in Section 5 and will dictate the communication requirements in terms of communications range, speed and security. The communication technologies and protocol stacks will then be selected accordingly as part of the work in task T4.1.

The major requirements driving the networking are related to the data delivery quality of service (Req.: 2.4; 4.5; 10.2).

3.2 Data Storage and Exchange Middleware

Most of the requirements defined in the D2.4 document reflect that e-balance system needs to have a database system to store the information related to historical sensor data, configuration data, management data, DSO data, aggregator data, customers’ data, weather agencies data, energy supplier data, energy retailer data, city municipality data and ICT provider data. Similar to the networking, these requirements define that the data has to be provided reliably and timely according to a defined quality of service (Req.: 2.4; 4.5; 10.2). Additional requirements defining the protection of the stored and exchanged data are addressed in Section 3.3.

Currently, any kind of system uses databases to store the data generated during their performance due to the benefits they provide:

- Avoid data duplication.
- Avoid inconsistent records.
- Easier to change data.
- Easier to change data format.
- Data can be added and removed easily.
- Easier to maintain security.
- Substantial time savings.
- Scalability.

The e-balance project presents a hierarchical architecture (four levels) where each level has certain independency from the rest. For this reason, it is advisable that each level is able to store its own data (user data, sensors data, appliances data, etc.) and only centralize in the Top level grid management unit the most relevant information. This way the information generated by one level in the e-balance system is only transmitted to the relevant levels and not propagated to the whole system. This hierarchical architecture approach helps to reduce the network traffic and to simplify management tasks as information is local to where it is needed. Figure 8 shows the architecture proposed to store data at different levels.

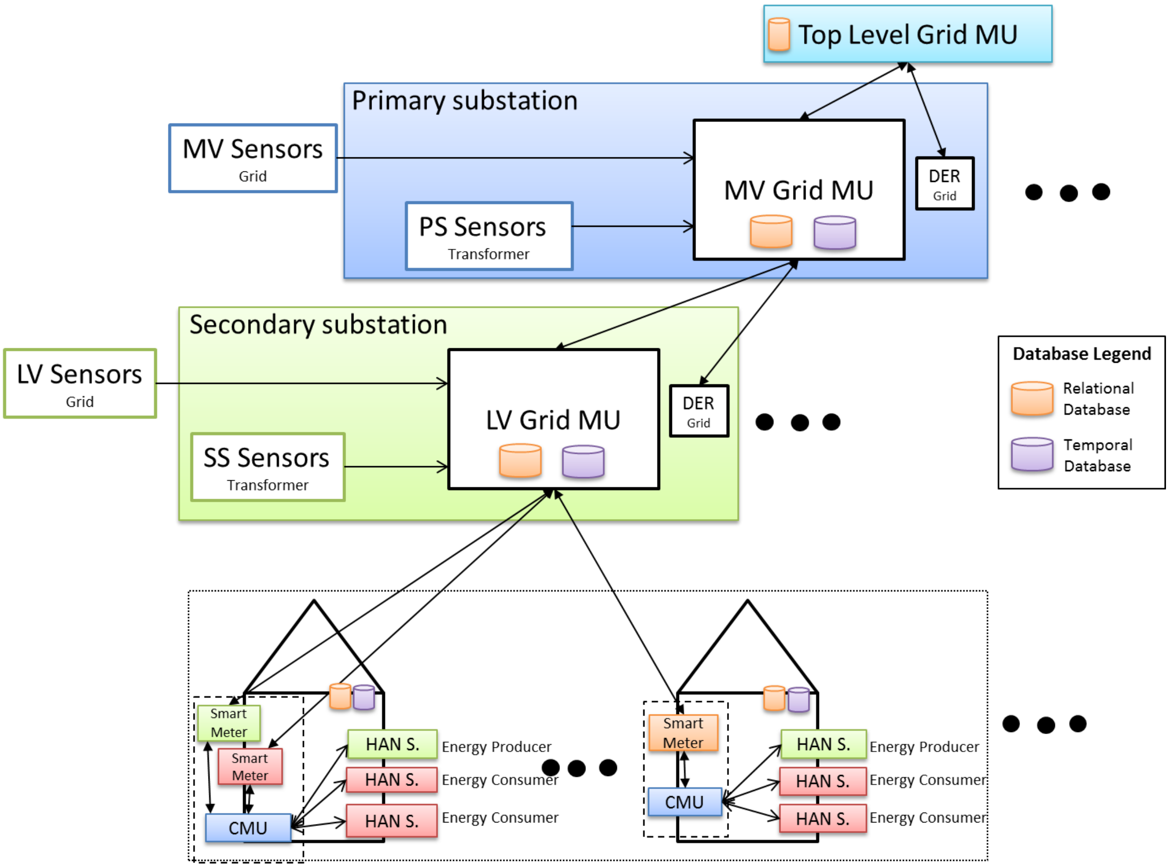

Figure 8: The e-balance data storage architecture

In terms of data storage, there are several important issues that need to be taken into account when designing a communication framework for Smart grids. Smart grids are a critical infrastructure and therefore data storage must be handled providing a set of Quality of Service (QoS) requirements such as security and reliability. On the other hand, the data that is sent through the communication platform determines the data storage functional requirements. In other words, the data that is going to be stored in the middleware is determined by the information flows between the management units of the e-balance system.

In general terms the data storage system is a distributed storage system where each management unit stores local data, either collected from sensors or generated based on information existing in the data storage system. Ideally, each management unit only has access to management units located in the following upper or lower layer although it can additionally query external services or devices if necessary, such as a weather broadcast provided by the weather agency. Each management unit is in charge of collecting data or receiving the events raised by other management units based on their interests and storing the needed information. A first proposal for the kind of storage of each management unit and the general information it needs to keep based on the uses cases identified in deliverable D2.1 and requirements from deliverable D2.4 is shown in Table 1.

Table 1: Management unit data storage

Management unit	Data storage technology	Data storage size	Information	Comments
Device MU	Volatile and non-volatile	Small	• Device identification • Device parameters • Device features • Device state • Sensor readings • Control registers	Implementation of the device storage is appliance vendor specific and connected with the e-balance platform via the smart appliance interface.
HAN sensors	Volatile	Small	• Sensor readings • Sensor configuration	HAN Sensor readings are not permanently stored
Consumer MU	Database (embedded database)	Medium	• Home area network sensor readings • Consumer information (strategies, energy consumption, configuration parameters, etc.) • Electrical appliance information (consumption, connect/disconnect electrical appliance, etc.) • Aggregator information (agreement, strategy, etc.) • Grid status (energy limitations, energy supply status, etc.) • Socioeconomic parameters (energy costs, prices, energy source – CO_2 emission, etc.)	
Low voltage grid MU **Medium voltage grid MU** **Top level grid MU**	Conventional Database	Big	• Low voltage grid sensor readings • Consumer information (strategies, energy consumption, configuration parameters, etc.) • Energy market information (energy price, contract information, energy predictions, etc.) • Low voltage grid status (device status, failures, logging, etc.) • Aggregator information (agreement, strategy, etc.) • Regulatory information (energy price limits, connection point limits, energy and power restrictions, etc.) • Grid information (energy limitations, energy supply status, grid topology, etc.) • External information (city municipality, weather agency, etc.) • Socioeconomic parameters (energy costs, prices, energy source – CO_2 emission, etc.)	

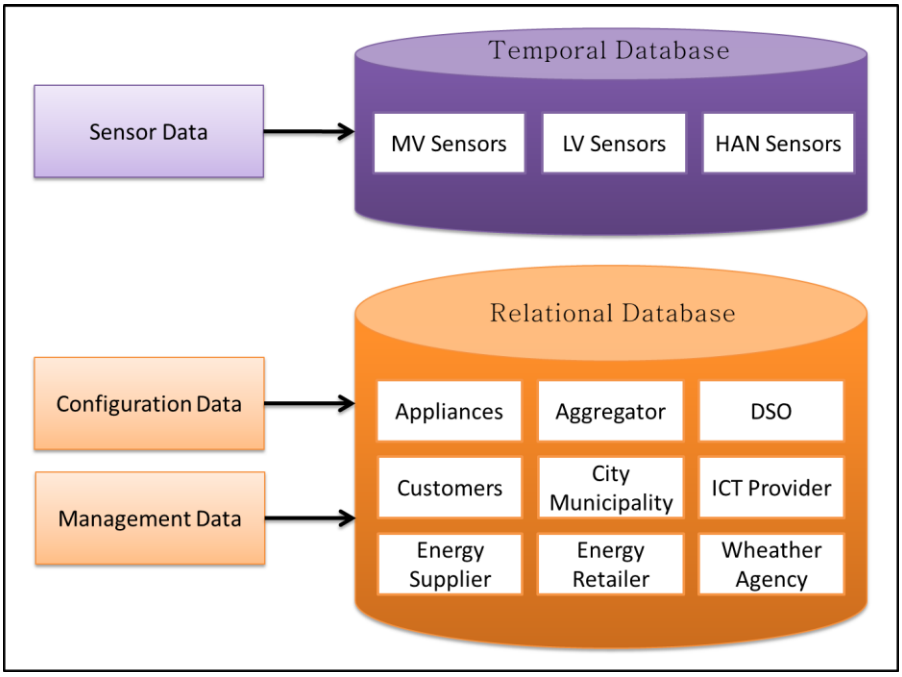

Figure 9: Configuration of databases

The e-balance system will have to be able to store two kinds of data: sensor and configuration data, in which their intrinsic features make them different. For this reason the data-storage architecture introduces two different types of database: Temporal and relational databases (see Figure 9). The former is specially designed to manage and store time series data (arrays of numbers indexed by time), such as for example information coming from sensors. These databases not only are able to store a huge amount of data but they are also very scalable and flexible, which means that if in the future new kinds of sensors are installed, the system will allow to store their data easily. The latter are the traditional databases, which are typically used to store structured information such as configuration data.

3.3 Security and Privacy Mechanisms

The security and privacy mechanisms in the communication platform can be regarded as library providing specific functionality that is used by the main system components, i.e., the networking and the data storage and exchange middleware. Additionally the security mechanisms support the node protection and maintenance. Thus, depending on the component they support these mechanisms are responsible for different aspects of the functionality:

- Node level protection and maintenance

  In order to allow stable and secure operation of the units several security-related functions are required on the node level. These include a code update mechanism, unit parameterisation and reset mechanism to support unit maintenance as well as node protection mechanisms that, e.g., monitor the execution of the code. All these mechanisms allow putting the unit and its software into a stable state in case of failures or errors. This functionality defines the ground for the security and privacy mechanisms mentioned in the following paragraphs.

- Communication (network) security and privacy mechanisms

  The network security mechanisms shall provide mainly data confidentiality and data integrity in the network (Req.: 2.4; 4.5; 6.9; 10.2; 12.1; 13.3; 18.10; 23.2; 23.4; and L7.1).

  The data exchanged in the network shall be protected against modifications and unauthorized access. This applies for (almost) all the data in the system, including the user personal data, companies' business data, as well as for information like weather forecast that is provided by some service agencies. The only exceptions may be data that is meant to be openly broadcast on purpose.

Thus, the main aim of the security and privacy mechanisms on this level is to protect the communication between the units. This shall be done by message protection and unit authentication. The means to realize this functionality are scalable cryptographic mechanisms and security protocols based on these, like key exchange protocols and public key infrastructure approaches required for the use of certificates, including certificate revocation.

- Middleware security and privacy

  The main aim of the security and privacy mechanisms used by the middleware is to provide access control to protect the stored and exchanged data from unauthorized accesses. This includes the control while accessing the data for reading (Req.: 8.4; 12.2) as well as while writing values that influence the system behaviour, e.g., changing the user strategy (Req.: 1.9; 3.5; 4.4; 5.12; 6.11). The personal information that is not measured directly, but derives from the measurements is personal data as well and has to be protected as well (Req.: 19.2; 20.1). This level of protection is to be realized for each data item individually based on the privacy settings defined by the users and it assumes that the instances of the middleware located at distant units exchange data using a protected communication channel.

  The user's privacy settings for a given data item shall be monitored and in case they do not allow access to the given data item or the period for storing the data item expired, appropriate actions will be triggered, like denial of access or removing the data item from the data storage (L9.1).

  Further, in order to make the data available for other purposes than defined by the user, mechanisms to anonymize the data are necessary. These mechanisms have to make it impossible to link the data with the user identity (L12.3).

  The access to the user data via the GUI shall also be protected against unauthorized access (Req. 7.3).

  The user decides what data is allowed to leave the local instance of the middleware and be available to outside (Req.: 8.1; 8.2; 8.6, 12.4). The purposes the data may be used for are specified by the user as well. These user privacy settings have to be enforced by the privacy mechanisms. If other stakeholders (cooperating with the user) require a change in these settings, these may be negotiated (Req. 8.3).

  The operations within the Energy Balancing and Grid Control and Management components on the management units may be executed on behalf of diverse stakeholders, the check if this stakeholder is allowed to use the user data is done by the privacy and security mechanisms within the middleware.

  There shall be a defined stakeholder that is responsible for the execution and enforcing of the security and privacy mechanisms (Req. 8.7).

The privacy and security mechanisms on all the three levels have to comply with the legal implications and requirements specific for the country of deployment (L1.6; L1.7; L2.2; L3.1; L3.2; L5.1; L7.1; L8.1; L8.2; L10.1; L12.1; L12.2; L12.3; L13.1; L14.1; L19.1; L20.1; L22.1; L25.1; L25.2). Specifically, the privacy policy settings defined by the legal rules are to be taken as default settings. If the data is going to be recorded and, for instance to be used for simulations, it has to by anonymized.

4 Energy Management Platform

The energy management platform includes the functionality for energy balancing, energy prediction, grid control and monitoring and the security mechanisms. These will be presented in the following sections in detail.

4.1 Energy Balancing

One of the goals of the energy management platform is to take care of the energy balancing. The goal is that the energy production and consumption of the grid are balanced, such that energy is consumed as close to where it is produced, as possible. The economic and social aspects like the energy source and the overall costs of consumption and distribution shall be considered here as well. The balancing is realized on every level of the grid and it implies less distribution losses, controls peaks in energy consumption and helps to improve energy quality. As investments (power plants, cables, etc.) are made depending on the peak power, a reduced peak power implies a cost reduction. General information on the grid and its status is available, such that the algorithms and the customer can take this into account (Req.: 2.3; 5.9; 9.9). It depends on the legal situation of each country that is responsible on each level of the grid (Req. 12.5).

4.1.1 The Energy Prediction Mechanisms

In order to be able to do energy balancing a prediction of the produced and consumed energy is required (Req.: 1.10; 4.3; 4.14).

At each level in the hierarchy, the production and consumption for a defined time period, e.g., for the next 24 hours is predicted. The prediction is used to determine when there is a local shortage or surplus of energy. To balance this, the production and/or consumption of energy is shifted in time, or devices are controlled to adapt their production and/or consumption. The exact optimization objective depends on the strategy configured by the users, the priorities, the prices and parameters sent by the energy supplier / aggregator (Req.: 5.13, 5.14). The user can also influence the predictions, for example by choosing the source of the weather forecast (Req. 4.6).

4.1.2 The Energy Balancing Algorithms

To approximate the best possible results, mathematical programming techniques are used. These techniques take the predictions for the defined time period day as input and produce a planning as output. In e-balance, such planning is made hierarchically. A lower level network appears as a single entity to the higher level (Req.: 11.4; 11.5; 13.1; 14.1).

At the lowest level in the hierarchy, for the household, an optimal planning is made using mathematical programming techniques. Because the algorithms are executed on an embedded system (the CMU), they need to be efficient. Multiple types of devices are supported in the e-balance system. For example, household appliances whose functioning can be shifted in time, appliances of which the power consumption can be steered, e.g., batteries, Electrical Vehicle charging, etc. In work package WP5, we will design and develop algorithms to plan when the devices are active and what their settings will be. These algorithms that are executed on the CMU should take the user constraints, properties, economic and legal constraints of the devices into account (Req.: 5.3; 5.5; 6.4; 6.7).

At any higher hierarchal level in the network, the lower levels are asked for assistance to balance the energy consumption and production by using steering signals. When the energy is unbalanced, the Management Unit requests the management units (or devices) on the level below to make a planning that increases the energy consumption or production when it is too low, and to decrease it when it is too high. To balance the energy a steering signal is sent; a set of values for each time interval for the prediction period, to steer the behaviour of the underlying MU (Req.: 11.4; 11.5; 13.1). The exact form of the steering signals is to be defined in work package WP5, and depends on the research performed there. The controlled MU uses the steering vector to make a planning, which results in the expected energy consumption and production over the prediction period (called a power profile), and sends the power profile to the parent. This process is repeated until the parent obtains a satisfactory power profile. The number of iterations depends on the algorithm, the goal of the algorithm, the number of underlying MUs and the type of steering signals.

The planning step as described above gives (near) optimal results when the predictions that serve as input to the planning are correct. These predictions are likely incorrect as we must deal with unforeseen conditions due to human behaviour, weather, grid requirements, etc. (Req.: 9.5; 9.9). To cope with deviations from the schedule, we need a mechanism that deals with deviations that occur in real-time (Req. 9.4; 11.6). We call this *real-time control*.

The exact real-time control mechanisms and algorithms are to be defined in work package WP5, in task T5.2. They ensure that the energy balancing goals are reached, while respecting the schedule and unexpected events (Req.: 2.10; 2.11; 2.12; 4.13).

4.1.3 The Customer Strategy

On top of the energy balancing requirements and properties of the grid and the devices, the customer may set some requirements for the balancing algorithms in order to enhance his own comfort or profits (Req. 11.1). This customer’s strategy needs to be taken into account by the balancing algorithms (Req. 1.13).

The customer can define his personal strategies for how to use his locally produced energy (Req.: 1.8; 3.3; 3.4; 4.1; 4.2; 6.10), how to control his energy demand (Req.: 2.6; 2.7; 4.1; 4.2) while taking into account the limitations provides by the aggregator (Req.: 2.7; 2.9; 2.14), how to use energy storage (Req.: 5.1; 5.2; 5.4; 5.6) and how to use his EV for balancing purposes (Req.: 6.4; 6.5; 6.8). The customer may also decide to hand over the responsibility for the strategies to the aggregator (Req.: 1.9; 2.5; 2.13; 3.5; 4.4; 5.12).

When the customer’s objectives change, he may also change his balancing strategy (Req. 11.2). However, the number of changes should be limited to prevent an unstable grid (Req.: 1.4; 11.3).

4.1.4 The Accounting Mechanisms

In the balancing service, we assume that it will be connected to the existing distribution network with a smart metering advanced infrastructure, e.g., the InovGrid of EDP. This network is managed by the DSO/aggregator and it is possible to implement additional functionalities offered by this service. It means that this service expands on other subsystems, e.g., billing system, which operate and assure full integration and compatibility of all collaborating subsystems.

In D2.3 a price mechanism for proposed balancing service has been considered. The most important condition for the functioning of the mechanism of control signals and incentives are: a mechanism for dynamically variable price offers (Req.: 1.2; 2.4) and system information signals transmitted by the service from the aggregator to the client and vice versa, e.g., Automatic/Advanced Demand Response (ADR) (Req.: 2.2; 2.5; 2.8; 2.13; 2.14; 3.4; 4.4; 5.8; 9.6; 9.7; 9.9). It is assumed that these instruments will be sufficient mechanisms supporting rational and efficient customers’ balancing strategies in the balancing system and customers’ settlement (Req.: 4.9; 5.10; 8.5; 12.3). The mechanism of dynamic price offers and additional information signals are to inform the customer about the situation on the energy market, for example whether prices are currently high or low. According to the contract, they will be enabled to adapt, turn on/off or shift the use of smart appliances automatically (Req.: 1.8; 1.12; 2.1). The additional information about consumption and production forecasts and weather forecasts should help customer for better optimization and strategy decisions (Req.: 1.6; 4.3; 4.11; 4.12).

The e-balance Energy Management System (ebEMS) has to ensure a smooth, efficient and dynamic settlement of both: claims and payments for each customer according to the indications of reading meters and accounts, in order to obtain an optimal consumption of electricity produced locally and bill each month according to the actual readings. Calculation algorithms billing module must reflect the business model adopted for service balancing (Req.: 1.10; 1.11; 5.13; 5.14).

Considering the implementation of the test beds in real locations (Batalha, Bronsbergen), we have to develop the test conditions for pricing and tariffs, and a set of possible control signals for testing in almost real conditions.

4.2 Grid Control and Monitoring

4.2.1 Resilience and Self-Healing

Resilience is an attribute or, to be more precise, a goal of the Smart Grid. A resilient grid is able to cope with unpredictable events that might disrupt or disturb its normal operation, while offering the expected service, under predefined quality standards.

There are several steps to support a resilient grid, from an open and straightforward distributed architecture – as it is the case of the e-balance project – to the definition and selection of methodologies, tools and selected paradigms, which, when combined, offer the required outcome.

Grid resilience can be obtained by monitoring, meaning that whenever there is enough awareness of grid phenomena, human reaction can be boosted by adequate software applications supported by distributed sensors and other acquisition devices placed along the grid. Furthermore, the grid performance improvement can also be obtained by automatic features provided by distributed devices, combined within the e-balance Energy Management System – ebEMS.

Utilities have been deploying solutions for grid awareness and control with implicit automation features at distribution HV and MV grid levels. Presently, utilities are moving downwards, meaning that the deeper they go along the MV grid, the thicker the grid is, with an unprecedented amount of electric assets, from lines and cables to substations, all comprising power equipment.

The distributed intelligence belongs to a distributed monitoring, control and automation system which we call ebEMS. The ebEMS is based on the distributed intelligence paradigm, which uses an approach or system model where devices are deployed along the grid, supported by ICT. The ebEMS contributes to bringing dispersed data wherever it can be treated and used by remote devices (tools) for local grid automation and protection. Ultimately, it will be able to present recommendations to the management system operators for better managing the electric power grid. This will contribute to wider grid awareness, by means of sophisticated applications (tools).

A specific methodology that can be used at the MV level is self-healing. Self-healing relies on ICT infrastructures and on distributed automation devices, dispersed along the grid, coping with local / neighbourhood phenomena or with global phenomena. The ebEMS offers a comprehensive range of Smart Grid features able to cope with such phenomena, improving grid resilience. Specifically, the ebEMS will be able to provide fault detection, isolation and service restoration. It considers multiple alternative power sources, dealing with and controlling grid topology. Furthermore, it copes with a grid segment's capacity commitment, while maintaining voltage profiles. It also considers protective equipment driven by protection devices and switching equipment driven by grid sensors. Finally, it also deals with load transfer criteria and with dispersed generation and storage assets.

Self-healing aims at promptly mitigating the number of non-supplied customers (or non-supplied energy), while meeting all targets established for grid balancing and operation, serving all grid stakeholders. The extent of deployed features and of system response relies on the versatility and performance of the ICT infrastructures.

In short, self-healing is a way to achieve grid resilience. In real field applications, it deeply relies on ICT infrastructures and on distributed automation devices; therefore, its scope and extent will always be determined by the amount of investment assigned for deploying such kind of solutions.

At the MV level, even at the lowest voltage levels, it is possible to achieve “good value for money” solutions provided that their deployment observes critical and strategic grid nodes, especially those where it is common to find grid disturbances or contingencies affecting its normal operation and the expected standard service quality Key Performance Indicators (KPI). Besides, it must follow the distributed intelligence paradigm as well as the use of combined tools.

Presently, at LV level, it is not possible to implement self-healing methodologies simply because there is still no trend for heavy deployment of actuators over that segment of the distribution grid. This constraint arises from the fact that such deployment is not affordable due to the amount of investment needed to be carried out on local actuators and the corresponding ICT infrastructure, which, with the lack of incentives, contributes for such circumstance. Nevertheless, local awareness and resilience support is enough to contribute for MV self-healing, which has been placed in the Smart Grid agenda, although there is plenty to do, namely the solutions envisaged by the e-balance project.

The next sections describe with more detail the concepts and overall ideas described so far, aligned with the representative Use Cases which were already selected.

4.2.1.1 e-balance Energy Management System

The ebEMS corresponds to a wider solution, combining multiple components (equipment, devices, ICT, solutions). Figure 10 depicts an overall grid overview and the contributing system components.

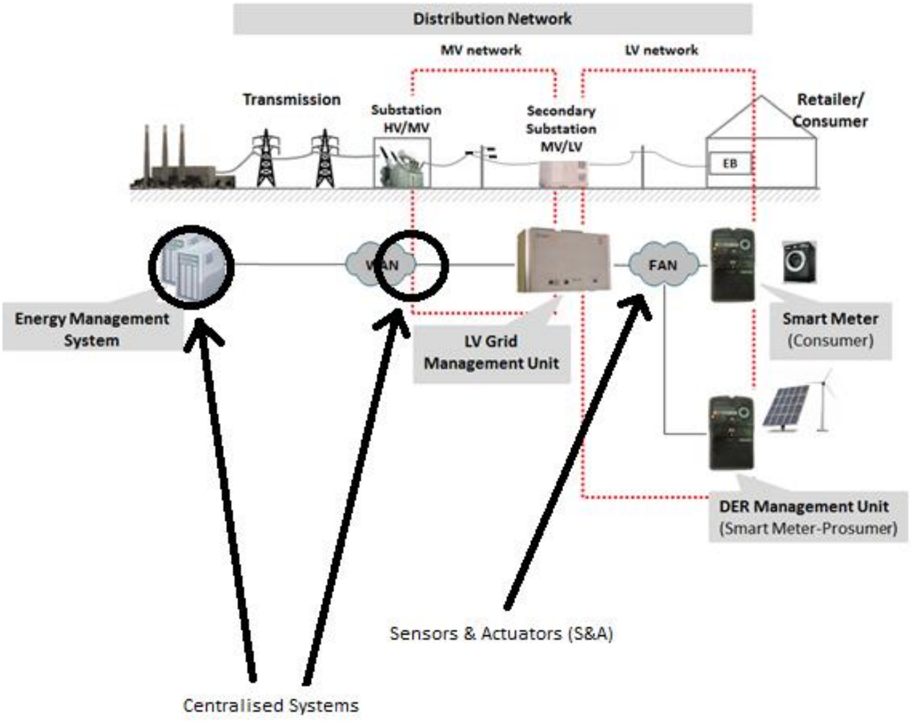

Figure 10: Overall grid overview and the contributing system components

Figure 11 depicts a closer view of the LV grid and the contributing system components, highlighting the LV Grid Management Unit responsible for performing advanced applications by smart solutions, using relevant data by Smart Meters and Sensors for power flow recognition (Req.: 13.3) and performing set-point control orders over the grid's DER via Actuators (Req.: 14.3; 14.4). Sensors and Actuators (S&A) are key components for any incursion towards LV grid automation.

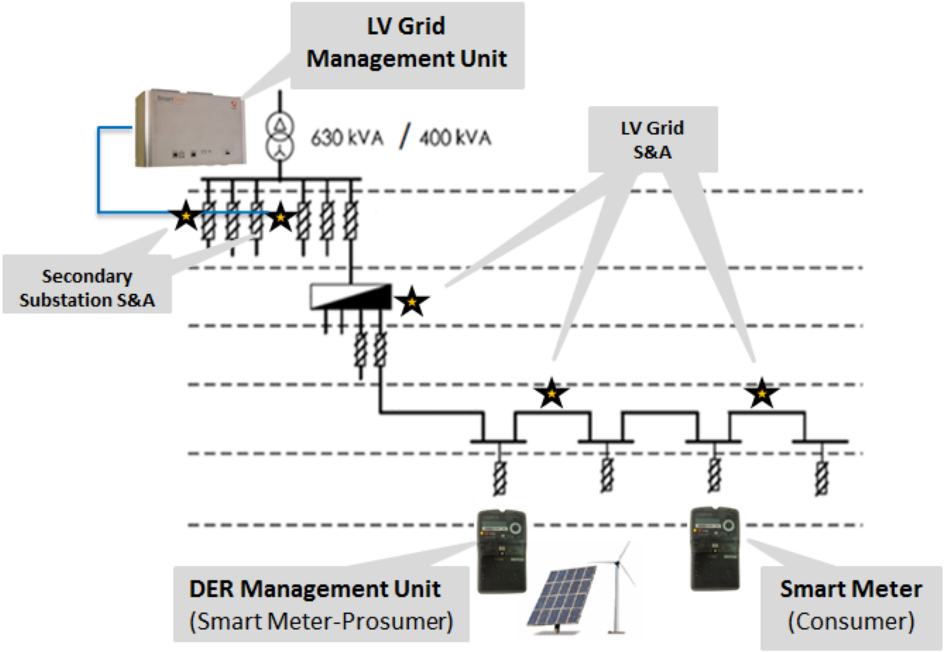

Figure 11: Closer view on the LV grid and contributing system components

Table 2 presents an overview of e-balance's system units and their relation with the selected Use Cases and the target functionalities. The Use Cases reflected in the table are those related to grid control and monitoring.

Table 2: The e-balance system units in resilience and self-healing

e-balance's System Units	Unit functionalities based on use cases (UCs)
Top Level Grid Management System	Optimized Power Flow (UC 15) Economic Dispatch (UC 16) Power Flow State Estimator (UC 17) Quality of Supply measurement (UC 18) Fraud detection (UC 20) Losses calculation (UC 21) Fault prevention (UC 24)
MV Grid Management Unit	Quality of Supply measurement (UC 18) Fraud detection (UC 20) Losses calculation (UC 21) Fault prevention (UC 30) MV fault detection and location (UC 29) Automatic grid service restoration – self-healing (MV) (UC 31)
LV Grid Management Unit	Quality of Supply measurement (UC 18) Fraud detection (UC 20) Losses calculation (UC 21) LV fault detection & location (UC 22) Fault detection on fused luminaires (UC 23) Fault prevention (UC 24) Automatic grid service restoration – self-healing (LV) (UC 31)
LV Grid or Secondary Substation Sensors & Actuators	Neighbourhood power flows (UC 13) LV fault detection & location (UC 22)
Smart Meter	Neighbourhood power flows (UC 13) Energy efficiency measurement (UC 19) LV fault detection & location (UC 22)
DER Management Unit	Energy efficiency measurement (UC 19) Distributed generation power flows (UC14)

4.2.1.2 Neighbourhood Monitoring

These features aim at providing grid resilience by means of using local grid awareness. Within the e-balance project, this feature is particularly assigned to the LV and MV grids. Neighbourhood monitoring covers all features aiming at boosting grid resilience. Grid resilience can be achieved by:

- Preventing the occurrence of contingency conditions impacting negatively on the grid (Req.: 24.1; 24.2; 24.3)
- Anticipating that occurrence (Req.: 13.3; 14.3; 14.4)
- Reacting upon occurrence (Req.: 22.1; 22.2; 22.3; 22.4; 22.5; 22.6; 23.1; 23.2; 23.3; 23.4; 23.5; 23.6; 23.7).

The next sections describe what e-balance intends to provide as application requirements for grid monitoring.

In [2], it is proposed a neighbourhood-like model for MV grid monitoring, featuring a combined self-healing holistic approach, based on a distributed architecture.

4.2.1.2.1 Power Flow Recognition

Power flow recognition is an important feature as it provides an insight of the real time grid behaviour. Grid measurements such as grid segment currents and power flows (active, reactive), grid node voltages, energy and power factor are key data needed to accomplish such grid awareness (Req.: 13.1; 13.2; 13.3; 14.1; 14.2; 14.3; 14.4). Besides, grid topology state awareness is also a key issue (Req.: 17.1; 17.2; 17.3; 17.4).

The challenge at distribution level is how to deal with synchronized (or time related) data. A neighbourhood approach with local sensors is able to deal with such time synchronization constraint, provided that enough algorithmic resources are available locally. These are key target resources for e-balance, as its holistic grid management approach – the ebEMS – comprises distributed processing, yet under hierarchical related component architecture.

Power flow recognition grants the EMS system and their users with enough data for taking the correct steps, automatic or as a response to human decision. At LV level, as there are customers and DER assets, comprising Distributed Generation (DG), Combined Heat and Power (CHP), Electric Vehicles (EV) and storage, there is a need for local power flow awareness. Thus, by using LV grid sensors and smart meters placed at customers, as well as placed in DER assets or their managing infrastructure, this neighbourhood concept is feasible, provided that a LV grid management unit gathers and tags all related data, dealing with measurements, grid topology and alarms. Furthermore, it can assess the local demand as opposed to the available energy sources, either from DER or at the secondary substation level. Energy profiles, at this substation level or at each measured node, boost a comprehensive awareness (Req.: 15.4) of the neighbourhood assets, also under a historical perspective (Req.: 15.5; 15.6), able to provide services which will be described in the next section (Req.: 15.1; 15.2; 15.3).

Grid power flows at neighbourhood level, also comprising DER, can thus be used by higher level management units, either at MV or at the grid top level. These management units (at MV level and/or top level) may use the available data to optimize the power flows, meaning that grid topology may be reshaped so that an optimized grid use is achieved (Req.: 15.1; 15.2; 15.3; 15.4; 15.5; 15.6; 15.7; 15.8). This achievement has to deal with grid constraints (power flows in specific segments due to their nominal capacity), voltage levels, while balancing grid energy sources with demand, in all hierarchical grid levels. Topology management also improves loss reduction, minimizing the cost per delivered energy. All safety and grid code criteria have to be taken into account.

There are energy sources dispersed all over the grid, providing grid services, comprising energy to be injected when needed. Those sources may be of several types, ranging from fuel powered to renewables. The challenge of dealing with demand and generation balancing will be solved by combining the mentioned features with an economic dispatch feature. This feature computes the expected demand for a certain timeframe, using available or predicted (from historical) data, and defines power control set-points which will be sent to all generation assets (Req.: 15.7), aiming at balancing the grid, while meeting the already mentioned criteria and minimizing the grid overall costs (Req.: 16.1; 16.2; 16.3), from a generation (fuel) and operational (losses) perspective. Special care should also be taken when dealing with renewable generation assets which participate in the grid under a specific business model, where penalties could be envisaged.

All of the previous makes sense under the perspective of a perfect grid data snapshot, which does not exist. In fact, if neighbourhood approaches mitigate the negative impact of lack of synchronized (obtained within the same timeframe) data, once the computational effort is brought up in the management system hierarchy, the more the impact of that lack of synchronization is. A state estimator deals with this issue and solves it. In [3], new approaches for dealing with grid lack of observability and non-synchronized data are presented.

All of the previous is feasible, provided that different candidate topologies are assessed and validated, coping with the mentioned criteria and with the energy demand and the available capacity, from conventional (fuel powered) to renewable. A power flow state estimator will make such assessment, by validating those candidate topologies against the current real world grid state. A rank of topologies will allow choosing the one that best fits the optimization criterion.

4.2.1.2.2 Distribution Grid Monitoring

As mentioned in the previous section, power flow recognition allows obtaining a comprehensive awareness of the neighbourhood assets, also under a historical perspective, which can be used for fraud detection.

Consumer patterns, from a historical perspective, combined with load curves from each consumer and from the energy totals available at MV secondary substation level, correspond to pertinent data which can be assessed, under the supply profile by all energy sources (the grid, RES), so that fraud detection could be accomplished (Req.: 20.6; 20.10; 20.11; 20.12). This fraud detection needs also to include data from all sensors across LV feeders, providing LV grid awareness.

But fraud is not a demand issue only. It also impacts on fake distributed generation, so out of scope generation patterns will be assessed as well.

This feature comprises establishing criteria for classifying LV grid behaviour, comprising both consumers and micro-producers (Req. 20.1; 20.2; 20.3; 20.4; 20.5; 20.7; 20.8; 20.9; 20.13).

Similarly, assessing LV grid behaviour with the mentioned data is a key feature for enabling grid inefficient use, comprising losses calculation (Req. 21.3). Again, energy historical and real time use, comprising local LV grid and consumer energy patterns, together with distributed sensor data offer a valuable set of information for losses calculation (Req.: 21.1; 21.2).

Efficiency is not only an external customer issue. Indeed it is a grid issue, already described, but the ICT infrastructure at neighbourhood level can interface the inner customer world, via the smart meter, combining useful data from the typical customer energy use pattern, against an inside view of the energy used by each customer, which can be routed via the smart meter to the LV Grid Management Unit (Req.: 19.1, 19.2). Specific metrics of energy use, either at neighbourhood LV grid level or customer level have to be defined, serving the involved stakeholders such as the utility/DSO itself, the city municipalities and the national regulators (Req.: 19.3; 19.4; 19.5).

Each electric power utility has its own service quality and energy quality indices, although international standards normally apply. Such indices are commonly calculated at MV level, but, with the grid management paradigm envisaged by e-balance, a closer look on the LV grid performance can also be feasible, through the definition of KPI (Req.: 18.8; 18.9).

Therefore, KPI will be defined, comprising service interruption times, grid availability and customer service availability, duration and frequency averages related to outages and other contingencies. Furthermore, and by means of appropriate sensors with enough precision, electric power quality (harmonics, voltage dips) can also be assessed at LV grid level in this neighbourhood perspective (Req.: 18.10; 18.11; 18.12).

KPI reporting will be available for concerned stakeholders such as the utility/DSO itself, the city municipalities and the national regulators (Req.: 18.1; 18.2; 18.3; 18.4; 18.5; 18.6; 18.7; 18.13; 18.14; 18.15).

4.2.1.2.3 Fault Detection, Location, Isolation and Restoration

These features aim at providing grid resilience by means of using local grid awareness to promptly react upon the occurrence of distribution grid faults. Furthermore, the end users (customers) play an important role as they aim at being informed about the duration of any outage and of the corresponding repair/maintenance time and status (Req.: 22.1; 22.6).

Fault detection relies on fault current sensors deployed along distribution feeders, normally at MV level but also able to be deployed at LV level (Req.: 22.2; 22.3). Their placement imposes a certain level of current transducer precision, so that currents within a certain range could be read, offering valuable data on their normal or abnormal state condition, trend, etc. Specific transducers for fault currents, up to 4 times the nominal current may be envisaged as well, or, as an alternative, if nominal range transducers are those only used, then when they saturate it means that the sensor is in the presence of an exception current which can be tagged as a faulty current. In this case, a signal of fault current detection could be enough, which detection upon fault occurrence is of valuable interest.

As said, those fault current sensors are deployed along the grid feeders, either at MV or LV grid level. They rely on ICT infrastructures; therefore, the data describing the fault is processed by smart solutions deployed upstream, dealing with their own awareness of the grid topology, with the placement of the fault sensors and with the fault data arising from them.

When deployed at secondary (MV/LV) substations, these smart solutions, installed at the LV Grid Management Unit, serve the purpose of dealing with LV faults. Combining topology data together with fault data, they are able to provide fault detection and location (Req.: 22.4; 22.5), thus improving maintenance team response, so that the downtime of the affected grid segment is reduced, by speeding up any due corrective intervention.

Similarly, fault detection and location features over public lighting will also be supported by ebEMS, as these LV power segments share the same phenomena as those at conventional LV grid level. Besides, detection and location of fused luminaires will also be addressed within ebEMS (Req.: 23.2; 23.3; 23.4), as well as detection of anomalous behaviour of the luminaries segment (Req.: 23.5; 23.6; 23.7). Public lighting may be managed by the DSO, but also by municipalities, therefore the latter is an important stakeholder also involved in the mentioned features (Req.: 23.1).

As a result of the LV grid awareness (Req.: 24.1), the ebEMS will be able to extract data so that a risk analysis (probability of failure) over the LV assets (overhead and underground grid segments, distribution cabinets, MV/LV transformer, fuses, etc.) could be achieved in the form of fault prediction (Req.: 24.2). ebEMS will be able to report assets prone to failure, under the current grid conditions, ordered by ranking of probability (Req.: 24.3).

All these approaches apply also for the MV grid, this time by deploying smart solutions at primary (HV/MV or MV/MV) substations, which, in turn, are installed at the MV Grid Management Unit and are able to understand the downstream topology of all MV grid segments. These MV grids offer ways to install intelligent switching and protective equipment along strategic nodes, with the ability for remote and automatic control, thus suitable for grid topology changes.

When deployed at primary substations – or even at central systems – these smart solutions serve the purpose of dealing with MV faults. Combining topology data together with faulty data, they are able to provide fault detection and location, as well as automatic procedures to isolate faulty segments and to restore grid service via other feeding points, without affecting the overall service, respecting grid stability and expected maximum nominal current and voltage values, reducing the impact of the fault to the affected grid segment only. Off course this solution also speeds up any due corrective intervention, in a similar way as described above for the LV case.

Going back to the LV case, isolation and restoration are not common practices, particularly because LV grids have not been prepared for that purpose, meaning that at LV level, grids normally are not equipped with motorized actuators able to disconnect or switch grid topology, reshaping it or disconnecting it under a certain criteria. Provided such actuators and multiple in-feed LV sources are available, a smart solution deployed at a secondary substation, similarly as those expected to be placed at primary substations, will offer grid isolation and restoration features as well, provided that all safety rules coping with repair teams and assets are granted.

Table 3 shows the current trend and expected effort for deploying the Fault Detection, Location, Isolation and Restoration (FDLIR) features.

Table 3: Fault detection, location, isolation and restoration grid matrix

FDLIR Grid Matrix	MV Grid	LV Grid	Comments
Detection	Yes, current practice	Yes, feasible	Reliance on ICT infrastructure for deploying upstream applications with “wider grid awareness”
Location	Yes, current practice, yet prone to improvement	Yes, feasible	Those “wider grid awareness” applications can predict the faulty segment location by combining fault data with topology status data This feature is combined with the previous feature
Isolation	Yes, current practice, yet prone to improvement	Yes, feasible, although this is not a common practice by utilities	It needs switching devices able to disconnect/reshape the LV grid If remote controlled, their actuation can be performed automatically by those applications through the ICT infrastructure This feature is combined with the previous features
Restoration	Yes, current practice, yet prone to improvement	Yes, feasible, although this is not a common practice by utilities; yet, it needs further improvement for safety reasons	It needs further injection sources, e.g. from at least another LV feeder within the same secondary substation, or from another secondary substation’s LV feeder This feature is combined with the previous features. Restoration, if automatic – assuming that there will be enough actuators – will have to face new safety rules for dealing with both equipment and human intervention under LV faulty incidents.

4.3 Security and Privacy Mechanisms

The security and privacy mechanisms applied in the energy management platform address two aspects. The first is the identification and authentication of stakeholder processes running on the management units accessing the data using the data storage and exchange middleware. This aspect is a counterpart to the security and privacy means applied in the communication platform. Here, cryptography mechanisms corresponding to the computational power of the management unit are used to authenticate processes and to provide non-repudiation.

The second security aspect is related to the further data and privacy protection. The values shared via the middleware can be further protected by cryptography means, like encryption or privacy homomorphism.

The functionality of the security and privacy mechanisms in the energy management platform is driven by the same requirements as the security and privacy mechanisms applied in the communication platform, but focuses on data protection and privacy.

4.4 User Interface

The Graphical User Interface (GUI) plays an important role in every system. It collects the user inputs and presents the results together with the state of the system. A user friendly interface simplifies the use of the system and increases the user acceptance. In the e-balance system there may be a different GUI defined for different kinds of management units. The deliverable D2.4 defined a series of the requirements related to the GUI functionality.

The functionality and the way the data is presented on the GUI shall depend on the kind of user as well as the user preferences (Req. 7.1). The GUI shall be implemented based on defined (data) interfaces (Req. 7.2) that shall be protected against unauthorized access (Req. 7.3). All the user data shall be protected against malicious access and modification according to the privacy regulations (Issue L7.1).

According to several requirements (Req.: 1.1; 1.8; 2.1; 2.2; 2.6; 3.3; 3.4; 4.2; 5.6; 6.8; 9.1; 9.2; 10.1; 11.1; 11.2) the GUI shall allow the user to define the system working parameters (the strategy) in a user friendly way (Req. 1.5). The GUI shall show the current state of the system (Req.: 1.2; 1.7; 3.1; 3.2; 5.7; 9.3; 15.4; 18.11; 18.13; 20.8; 22.3; 23.6; 23.7) as well as other necessary information (Req. 1.6) allowing the user to define the system working parameters within the correct context. The GUI shall also analyse the provided input and do an initial check to avoid incorrect or incoherent settings (Req. 1.3). The spectrum of this check shall be defined further or be configurable. Due to some possible restrictions there shall be a defined system parameter that limits the frequency of strategy definition (Req.: 1.4; 11.3). The GUI can also be used to renegotiate the defined strategy (Req.: 2.5; 5.10). The GUI shall also allow the manual control for any stakeholder (Req. 15.7).

The user can also give away control using the GUI (Req.: 1.9; 2.13; 3.5; 4.4; 5.12), e.g., allowing the DSO or aggregator to influence the user strategy. In this case the user shall also be able to define the borders for the delegated control.

The GUI shall allow monitoring the current system state (Req. 4.7) and shall warn if the execution of the strategy is in danger (Req. 4.8) as well as present the costs of this situation (Req. 4.9). It shall provide the user with the possibility to change the technical system parameters (Req. 4.10) and make them available. Additionally, the GUI shall also provide the possibility for benchmarking, including self-feedback (Req. 7.4).

The privacy and security restrictions or policies that apply to the user data shall be adjustable and definable via the GUI (Req.: 8.2; 8.4; 8.6; 12.2; 12.4; 13.2; 14.2). This applies for all system stakeholders. Additionally, there shall also be an option for renegotiating these data privacy settings using the GUI (Req. 8.3). This renegotiation involves a service providing stakeholder and service user, where the service may be of any kind, e.g., energy or information. The user may for instance relax the privacy settings for some benefits.

There shall be also some GUI to the system simulator software in order to show the results of the performed simulations.

Figure 12 shows the architecture of a stand-alone user interface unit based on the general management unit architecture shown in Figure 4. In the most complex case, the user interface may be realized as a device equipped with the communication platform functionality allowing accessing the data storage and exchange middleware and the data interface provided by the middleware is used by the GUI that represents the energy management platform on the user interface device.

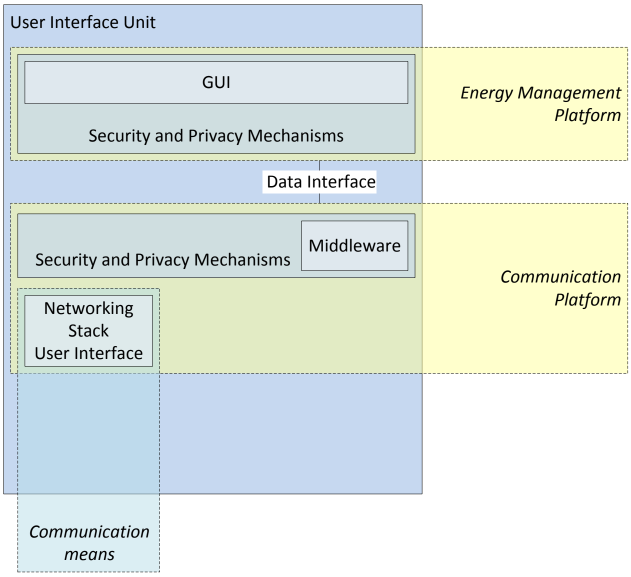

Figure 12: The architecture of a user interface device based on the general management unit architecture

5 Information Flows

This section gives a high level overview of the information flows within the e-balance system. Section 5.1 describes the information flows involved with the energy balancing. These traverse through the full hierarchy. However, the communication will be most intense at the lower levels where the devices are managed.

Section 5.2 focuses on the information flows used for grid control and monitoring. Since grid control and monitoring is done within the distribution level, the discussed information flows are between the management units and sensors within this level.

5.1 Energy Balancing

The energy balancing algorithms can only make good decisions depending on the information that is available, and must communicate these decisions. The communication infrastructure must support the communication of this information.

To communicate the steering signals, one value for each time interval must be communicated (Req. 4.15). For example, when 15 minute intervals are used, 96 values are communicated for steering signal to cover a prediction period of 24 hours. The response by the underlying management unit is a power profile, which is the average power consumption within each interval. In the above example this would again be 96 values. Other vectors (e.g., weather forecasts, prices, desired profiles, etc.) are also required and communicated by the algorithms. The algorithms may require some additional metadata that is sent together with the vectors, e.g., priorities of alternative profiles, depending on the algorithms that are developed in work package WP5. Because the algorithms are developed in work package WP5, the exact content and time resolution is to be determined later.

During the planning phase, at the beginning of the prediction period, each higher level management unit exchanges multiple vectors with each of its underlying management units. Weather forecasts and consumer level measurements can also be transmitted this way. All this information about the upcoming prediction period is used to make a planning, and the result is communicated to the controlling management unit (Req. 4.14). During the prediction period, the real-time control algorithms exchange such messages when an update is available (Req. 9.4).

To make the decision, the CMU must be able to control the appliances/devices (Req. 9.10; Req. 10.3). The CMU is capable of discovering devices and querying the device configuration (e.g., battery capacity, PV capacity, etc.). For each device the CMU stores the user settings (e.g., deadline for the washing machine). As the devices are dynamic, the devices send status updates to the CMU (e.g., the state of charge, selected washing program, etc.). The CMU can send device requests to each device (e.g., charging power, start/stop device, etc.). The device configurations, settings, status updates and requests are all dependent on the type and brand of device. An important project that describes interfaces for steering devices for DSM is FPAI, developed by TNO.

5.2 Grid Control and Monitoring

The system units under this description are the following:

- Centralised Systems, e.g.
    - The TSO SCADA/EMS system
    - The SCADA/DMS central system, as the Top Level Grid Management Unit
    - The Primary Substation (PS) placed MV Grid Management Unit
        - The PS sensors and actuators
        - The MV grid sensors and actuators
- The Secondary Substation (SS) placed LV Grid Management Unit
    - SS sensors and actuators
    - LV Grid sensors and actuators
- DER Management Units at all voltage levels

- Customer Smart Meter

The SCADA/DMS central system, as the Top Level Grid Management Unit (TLGMU) dialogues with the following systems, aiming at:

- The TSO central system (in literature referred as Energy Management System), by sharing pertinent data arising from the border of both transmission level and distribution level grids, as bulk generation in the former must comply with the demand needs in the latter. Besides, DER intermittent or expected behaviour at both sides needs to become visible to the other side, so that balancing mechanisms could be envisaged. Both parties share grid status and alarm data and, although both could send control orders, normally the TSO has the precedent, therefore it may send control orders to the distribution level, namely to the TLGMU, with impact on DER assets placed at this distribution level, via their DER Management Units. Any other orders may be interpreted so that the TLGMU decides which further actions it will take within its own grid scope.
- Each DER Management Units (DERMU) placed at MV grid level, setting new production levels by sending them set-point controls over the injected power for energy balancing and grid stability purposes, curtailing assets for grid balancing or security purposes if needed, and collecting production and condition monitoring status and alarm data, as well as grid node measurement status and alarm data.
- Each MV Grid Management Unit (MVGMU) placed at Primary Substations (PS). The TLGMU fully monitors all MV assets, either inside the PS or at MV grid level, with the possibility to override (a decision by a duly assigned TLGMU operator) any automation or control set to run autonomously at this level. This task comprises the use of sensors and actuators, respectively via the PS Local Area network (LAN) and the MV Field Area Network (FAN). At this level, monitoring means a complete collection of all monitored assets within the substation and the MV grid, comprising grid measurements status and alarm data. This full ability to collect data and to control the grid at this level, leverages an unprecedented potential for dealing with energy balancing, RES intermittent behaviour, load changes, MV grid contingencies, etc., jointly managed at TLGMU and MVGMU sides, suitable for self-healing features deployment.

MVGMU placed at PS is able to monitor and control its own grid scope, as described, namely the substation equipment (circuit breakers, switches, transformers) and the downstream MV grid, comprising other equipment such as switches, reclosers, other MV/MV and MV/LV substations, DER assets and MV controllable loads. MVGMU dialogues with the following systems, aiming at:

- The TLGMU, as described.
- PS actuators and sensors, under a top-down/master-slave paradigm, although the current trend also envisages that PS actuators and sensors, comprising protective devices, could also establish peer-to-peer communications among them, via the PS LAN. MVGMU may perform similarly as the TLGMU. Indeed, normally all protection and automation devices respond with full autonomy within the scope of the PS which is managed by the MVGMU. In special cases and for setting purposes, TLGMU may override some pre-defined behaviour. The same kind of the already described grid measurements, status and alarm data is available at MVGMU.
- MV actuators and sensors via the MV FAN. As a result of the successful deployment of peer-to-peer communications within the PS LAN, a broad debate points out for also using such communication paradigm to handle distributed systems at MV grid level, combined with the PS master controller, which, in the e-balance project is the MVGMU. MVGMU may perform similarly as the TLGMU. Furthermore, MVGMU can be set to work with full autonomy, with no autonomy or under advisory mode by TLGMU. The same kind of the already described grid measurements, status and alarm data is available at MVGMU.
- Some DER Management Units (DERMU) with relevant installed power, placed at LV grid level, setting new production levels by sending them set-point controls over the injected power for voltage regulation purposes, curtailing assets for grid balancing or security purposes if needed, and collecting

production and condition monitoring status and alarm data, as well as grid node measurement status and alarm data.

- Each LV Grid Management Unit (LVGMU) placed at Secondary Substations (SS). The MVGMU fully monitors all LV assets, either inside the SS or at LV grid level, with the possibility to override (a decision by a duly assigned TLGMU or MVGMU operator) any automation or control set to run autonomously at this level. This task comprises the use of sensors and actuators, respectively via the SS LAN and the LV FAN. At this level, monitoring means a complete collection of all monitored assets within the substation and the LV grid, comprising grid measurements status and alarm data. This full ability to collect data from the grid at this level, leverages an unprecedented potential for dealing with energy balancing, RES intermittent behaviour, load changes, LV grid contingencies, etc., jointly managed at MVGMU and LVGMU sides, suitable for grid resilience deployment. As LV actuators are also envisaged, there is also a huge potential for deploying self-healing mechanisms at LV grid level, provided that alternative grid sources and grid topological flexibility exist.

LVGMU placed at SS is able to monitor and control its own grid scope, as described, namely and if applicable, the substation equipment (circuit breakers, switches, transformers) and the downstream LV grid, comprising other equipment such as LV switches and DER assets. LVGMU dialogues with the following systems, aiming at:

- The MVGMU, as described.
- SS actuators and sensors, typically under a top-down/master-slave paradigm, via the SS LAN. LVGMU may perform similarly as the MVGMU. Indeed, normally all control and automation devices respond with full autonomy within the scope of the SS which is managed by the LVGMU. In special cases and for setting purposes, MVGMU may override some pre-defined behaviour. The same kind of the already described grid measurements, status and alarm data is available at LVGMU.
- LV actuators and sensors via the LV FAN. LVGMU may perform similarly as the MVGMU. Furthermore, LVGMU can be set to work with full autonomy or with no autonomy by MVGMU. The same kind of the already described grid measurements, status and alarm data is available at LVGMU.
- Some DER Management Units (DERMU) with reduced installed power, placed at LV grid level, setting new production levels by sending them set-point controls over the injected power for voltage regulation purposes, curtailing assets for grid balancing or security purposes if needed, and collecting production and condition monitoring status and alarm data, as well as grid node measurement status and alarm data.
- Each Smart Meter placed at each consumer, collecting demand profile data, LV consumer grid measurement data. Furthermore, for balancing purposes, LVGMU may curtail the customer demand, fully or partially.

6 Summary and Conclusions

This document describes the e-balance system architecture at a high level. The e-balance system architecture is hierarchical and is based on energy management units in each level of the hierarchy. These units gather information that is available at a specific hierarchy level in the grid and employs this information to make energy balancing, energy resilience and self-healing decisions.

For energy balancing the hierarchy of the e-balance system is used to efficiently optimise the energy consumption of a large fleet of houses, and to improve the power quality. This document describes the ICT infrastructure to attain proper energy balancing. This infrastructure consists of the energy management units that execute efficient energy balancing algorithms. A key property of the algorithms is that they need to communicate with higher and lower levels of the network. To support this, the energy management units in all levels of the grid are connected through a modern and efficient communication platform that is introduced in this document.

The resilience and self-healing mechanisms that are proposed in this document follow a similar approach. The e-balance system deploys distributed intelligence to cope with unpredicted events. For this, the e-balance project mainly focuses on the medium voltage and high voltage grids. The same ICT infrastructure described above for energy balancing is also used for resilience and self-healing.

In deliverable D3.2, we will describe the e-balance system architecture in more depth and give the technical details of the system. These technical details on the devices, communication mechanisms and algorithms will form the foundation of the work done in work packages WP4 and WP5.

References

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