Platone

PLATFORM FOR OPERATION OF DISTRIBUTION NETWORKS

Platone

PLATform for Operation of distribution NEtworks

D4.5

Mesogeia demonstration: report

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Abstract

In this report the scope and implementation of the Greek demo are presented, along with the Key Performance Indicators (KPIs) that quantify its success. The main tools of the demo, namely the State Estimation (SE) tool and the variable Distribution Use of System (DUoS) tariffs algorithm, are elaborated upon. Furthermore, the supporting hardware (Phasor Measurement Units) and software (Platone Open Framework, i.e. the Distribution System Operator Technical Platform and the Blockchain Access Layer) are presented, both as concepts and as applications. The KPI metrics are shown, along with the calculations that resulted from the actual demo run. Additionally, a brief presentation of the customer engagement activities organised by the Greek demo team is provided. The Greek demo is a benchmark for HEDNO, since it constitutes the first time that tools such as the SE algorithm and the PMUs are deployed, albeit on a limited scale, in the Greek distribution grid. Also, the outcomes of the variable DUoS tariffs algorithm form a robust consideration for any future consultation about regulatory changes in DUoS. The KPI calculations showed measurable benefits for the Distribution System Operator, while the modularity and customization of the Platone Open Framework as tested in the Greek demo proved itself a powerful tool in the hands of HEDNO.

Keyword list

DSO, state estimation, observability, flexibility, distribution grid, network charges**,** PMU, SMU, DUoS tariffs, Platone Open Framework, platform, Use Case

Executive Summary

"Innovation for the customers, innovation for the grid" is the vision of project Platone - Platform for Operation of distribution Networks. Within the H2020 programme "A single, smart European electricity grid", Platone addresses the topic "Flexibility and retail market options for the distribution grid". Modern power grids are moving away from centralised, infrastructure-heavy transmission system operators (TSOs) towards distribution system operators (DSOs) that are flexible and more capable of managing diverse renewable energy sources. In this regard, Platone with involvement of Italian, Greek, and German demonstrators is using blockchain technology to build the Platone Open Framework to create an open, flexible, and secure system that enables distribution grid flexibility/congestion management mechanisms, through innovative energy market models involving all the possible actors at many levels (DSOs, TSOs, customers, aggregators).

This Deliverable provides an overview of the Greek Demo setup and validation framework utilizing the Platone Open Framework. The development of the tools and services within the project's framework is showcased, as well as the process and findings that resulted from the installation of five Phasor Measurement Units (PMUs) at the Mesogeia demo site. The results are presented in relation to the Use Cases (UCs) that were already established in the beginning of the Platone project and the Key Performance Indicators (KPIs) that were defined and updated during the project's lifetime. Additionally, the customer engagement activities organised by the Greek demo team are discussed, including key findings.

The results demonstrate the significant impact of the Platone Open Framework, which can effectively address challenges faced in existing distribution systems such as reduced grid reliability, security issues, and managing the increasing penetration of Renewable Energy Resources (RES). The proposed Platone solution enables the activation of available flexibility by integrating RES and implementing active demand response schemes. The use of Blockchain technology for information exchange and validation adds an extra layer of security.

The real innovation of the Greek demonstration lies in the proposed variable Distribution Use of System (DUoS) tariffs scheme, which, through extensive simulations, proved capable of capturing and exploiting the variability of the energy sources and consumption through specific patterns. Thus, with the use of just a few DUoS tariff patterns a significant cost reduction in distribution network operation is achieved, by harvesting the available Distributed Energy Resources (DERs) flexibility. The successful implementation of this scheme was made possible by the State Estimation (SE) tool developed within Platone, since the estimated state of the network is a prerequisite for the operation of the variable DUoS tariffs design tool. In this regard, integrating PMUs into the existing metering infrastructure significantly enhanced grid state estimation precision. Another crucial finding indicates that using the estimated state of the network as the input for the algorithm of optimal DER control, yields similar efficiency as knowing the true network state. Particularly, the implementation of the optimal DER control algorithm—embodied in the proposed variable DUoS tariff design—unveiled substantial benefits through flexible consumer engagement. This advantage was evident in Day-Ahead market and Real-Time scenarios, including TSO frequency support requests. Even with a small clustering (4-day types), effective variable DUoS tariff design captured grid condition variability adeptly. These tariffs prompted load shifting among consumers/prosumers in the test grid, preventing network limit violations and minimizing DSO intervention (generation/demand curtailment). Notably, the Greek demo affirmed the efficacy of the combined SE tool and optimal DER control algorithm.

In short, the combination and collaboration of the tools developed in the Greek demo within Platone Open Framework, prove that the provision of flexibility services to the Greek DSO can be made real in a future scenario of the implementation of a dynamic DUoS tariffs scheme.

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1 Introduction

The project "PLATform for Operation of distribution Networks – Platone" aims to develop an architecture for testing and implementing a data acquisition system based on a two-layer Blockchain approach: an "Access Layer" to connect customers to the Distribution System Operator (DSO) and a "Service Layer" to link customers and DSO to the Flexibility Market environment (Market Place, Aggregators, …). The two layers are linked by a Shared Customer Database (SCD), containing all the data certified by Blockchain and made available to all the relevant stakeholders of the two layers. This Platone Open Framework architecture allows a greater stakeholder involvement and enables an efficient and smart network management. The tools used for this purpose will be based on platforms able to receive data from different sources, such as weather forecasting systems or distributed smart devices spread all over the urban area. These platforms, by talking to each other and exchanging data, will allow collecting and elaborating information useful for DSOs, TSOs, Market, customers and aggregators. In particular, the DSOs will invest in a standard, open, non-discriminatory, blockchain-based, economic dispute settlement infrastructure, to give to both the customers and to the aggregator the possibility to more easily become flexibility market players. This solution will allow the DSO to acquire a new role as a market enabler for end users and a smarter observer of the distribution network. By defining this innovative two-layer architecture, Platone strongly contributes to aims to removing technical and economic barriers to the achievement of a carbon-free society by 2050 [1], creating the ecosystem for new market mechanisms for a rapid roll out among DSOs and for a large involvement of customers in the active management of grids and in the flexibility markets. The Platone Framework is tested in three European demos (Greece, Germany and Italy). The Platone consortium aims to go for a commercial exploitation of the results after the project is finished. Within the H2020 programme "A single, smart European electricity grid" Platone addresses the topic "Flexibility and retail market options for the distribution grid".

The adaptation of the Platone concept for its implementation within the Greek Demo has been carefully tailored to align with the specific needs and limitations of the Greek regulatory framework. Given the absence of an existing provision mechanism for the procurement of flexibility directly from customers, the Market Platform (MP) of the Platone Open Framework was not used. Instead, the Greek Demo focused on the utilization of the Blockchain Access Layer (BAL) and the Platone Distribution System Operator Technical Platform (DSOTP), which was the platform used for the exploitation of the software tools developed by the NTUA: the SE tool and the variable DUoS tariffs algorithm. The SE tool, hosted on the DSOTP, allows for advanced monitoring of the distribution network and provides the input for designing the variable DUoS tariffs for an entire year. Data from various measurement sources are harmonized, and then anonymized through the BAL. The deployment of the aforementioned platforms on the HEDNO server has been achieved using Docker container technology. In the following sections the Greek Demo is presented in detail.

1.1 Task 4.3 and 4.4

Task 4.3, "Ancillary services to TSO provided by the DSO", was initiated in the third month of the project's timeline (M3) and lasts until the project's conclusion (M48). The first part of this Task, namely the development of the algorithm, was successfully completed and the findings were reported in D4.3 [2]. More specifically, in D4.3 a tool based on a bilevel optimization model to provide Real-Time (RT) DUoS tariffs was introduced and tested using simulations. The current document reports on the completion of the second part of the task, concerning the validation of the algorithm in the Greek demo. For the purposes of this document the terms 'DUoS tariffs' and 'network tariffs' are used interchangeably to indicate the part of the network users' electricity bill which is attributed to cover the cost of installing, maintaining and operating the distribution network.

Similarly, the second part of Task 4.4, titled "Optimal control of DERs", which refers to the implementation of the algorithm developed in D4.4 [3] at the Mesogeia site, is completed and presented in this document. The results of the algorithm are shown in the present report and its feasibility is also assessed.

1.2 Objectives of the Work Reported in this Deliverable

The objective of this Deliverable is to present how the Greek Demo was set up using the Platone Open Framework. More specifically, the development of the tools and services within the project's framework is showcased, as well as the process and findings that resulted from the installation of five PMUs at the Mesogeia demo site. The results are presented in relation to the UCs established in D4.1 [4] and the KPIs defined in D1.4 [5].

1.3 Outline of the Deliverable

Following the introductory first chapter, Chapter 2 presents an overview of the Greek Demo objectives and a brief description of the pilot site, as well as the validation framework. Chapter 3 reports on the existing and Platone-related assets in separate subchapters, in order to highlight the innovative concept of Platone. Chapter 4 describes the methodology followed for the completion of the UCs defined in D4.1. Visualisation of the results is also provided in this chapter. Finally, the assessment of the revised KPIs for the Greek Demo, reported in D1.4, is presented in Chapter 5 and the customer engagement events carried out in the context of the Greek demo are summarized in Chapter 6. Chapter 7 concludes this Deliverable.

1.4 How to Read this Document

This report presents the final structure of the Greek Demo along with the results of the KPIs calculation, after a successful test of the tools and services that were developed within the project's framework. The Platone Open Framework, after its revision, is described in D2.2 [6]. Also, the platforms that were utilized in the Greek Demo, namely the Platone DSOTP and the BAL, are reported in D2.8 [7] and D2.13 [8] respectively.

Regarding the design of the Greek Demo, the definition of the UCs can be found in D4.1 and the KPIs definition, calculation methodology and data collection processes are described in D1.4 and D1.7 [9]. Regarding the tools and services of the Greek Demo, the SE tool is presented in D4.2 [10] and the algorithms for ancillary services to the TSO and optimal DER control are detailed in D4.3 [2] and D4.4 [3]. Finally, the customer engagement activities for the Greek demo are reported in-depth in D4.6 [11] and D1.5 [12].

2 Greek Demonstration overview

The value of Platone Open Framework for DSOs is multidimensional. The utilization of this Framework can bring several advantages to distribution networks. Specifically, within the context of the Greek demo, an improved version of low-cost PMUs combined with a SE tool, enables increased observability over the network's state, both spatially and temporally.

Furthermore, the tools and services offered through the Platone Open Framework strengthen the DSO's capabilities in a crucial era from an energy standpoint. By utilizing variable DUoS tariffs, developed by NTUA, DERs can be indirectly controlled in an optimal way, enabling flexibility provision services to the DSO. This offers great benefits, some of which are listed below:

- Demand Response Management: Flexibility allows the DSO to effectively engage with consumers and incentivize demand response programs. By implementing the variable tariffs scheme, thus providing cost-reflective price signals, DSOs can encourage consumers to adjust their consumption during peak periods or in response to system needs. This helps to mitigate extreme load fluctuations, avoid grid overloads, and potentially defer the need for costly infrastructure upgrades.
- Integration of RES: Flexibility is crucial for the integration of RES, such as solar and wind, which have a strong presence in Greece, and are inherently variable and unpredictable. By leveraging flexibility, DSOs can accommodate the fluctuating generation from renewables, ensuring grid stability and reducing generation curtailment.
- Enhanced Customer Engagement: Flexibility empowers customers to actively participate in the energy system and make informed choices about their energy consumption. By providing customers with few and simple tariff patterns, and the opportunity to benefit from demand response programs or other flexibility services, DSOs can enhance customer engagement and satisfaction.
- Decentralized Energy System: Flexibility enables the integration of DERs, such as rooftop solar panels, energy storage systems, and Electric Vehicles (EVs). By effectively utilizing these DERs and coordinating their operation, DSOs can transform the grid into a more decentralized and resilient energy system, reducing reliance on centralized generation and enhancing overall energy sustainability.

Overall, the effective utilization of flexibility by a DSO brings numerous benefits, including efficient grid operation, integration of RES, demand response management, cost reduction, customer engagement, and the promotion of a decentralized energy system. The remaining sections of this chapter provide an overview of the demonstration area and its characteristics, as well as the objectives of the Greek demo.

2.1 Mesogeia demonstration site

The Mesogeia area in the Attica region, which serves Athens as well as the islands Kea, Andros and Tinos, is the location of the Greek demo, which is led by the Greek DSO HEDNO and can be seen in Figure 1. The Mesogeia region encompasses a mixture of rural, urban, and suburban areas, providing electricity to approximately 225,000 customers through its Low Voltage (LV) and Medium Voltage (MV) networks, including households and small, medium, and large industries. The region benefits from various installations of renewables, including wind farms and Photovoltaic (PV) systems, such as net metering and rooftop PVs.

Figure 1: Mesogeia area.

For the purposes of the Greek demo, a portion of the Mesogeia area has been designated as the test site. Two radial distribution feeders, namely P210 and P490, originating from the Nea Makri HV/MV substation, have been selected for the installation of PMUs and the implementation of the Greek demo UCs. Both feeders deliver electric power via overhead lines with a nominal operating voltage of 20 kV. Overall, the test network consists of 338 nodes, each one representing a bus, and 337 branches, each one referring to a line connecting two buses. The composition of the node set is presented in Table 1.

Table 1: Description of nodes (type and number) of the test network.

Feeder	No. of nodes with injections			No. of nodes with zero injection	Total no. of nodes
	Slack bus	DER units	Load buses		
210	1	7	106	161	275
490	Common with 210	0	31	32	63
Aggregate	**1**	**7**	**137**	**193**	**338**

The common slack bus of the two feeders is identified as the HV/MV substation of Nea Makri and is used as the reference node when only conventional measurements are available. It is worth noting that a significant number of nodes correspond to zero injection buses, accounting for over 50% of the total number of buses. The individual substations of MV consumers and the MV/LV transformers form the load bus set. The configuration of the two feeders, as well as the structure of the HV/MV substation of Nea Makri are provided in Figure 2. The top of the feeders 210 and 490 are circled with dashed yellow line.

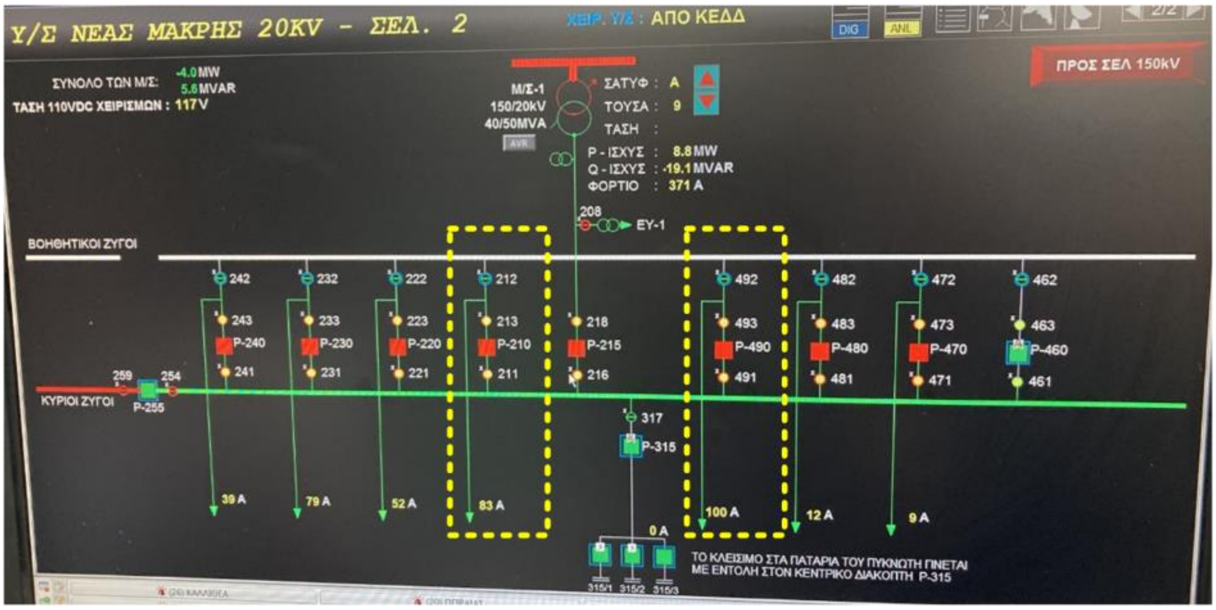


Figure 2: Configuration of Nea Makri substation.

The loads on both lines consist of households and small businesses located in rural and suburban areas. A dedicated optimization algorithm was used to select five different substations for the installation of PMUs, taking into account existing constraints. All five PMUs are installed on load buses of P210.

2.2 Validation framework for the Greek Demonstration

2.2.1 The value of State Estimation

Platone partners HEDNO and NTUA, via a joint collaboration within Platone, conceptualised the idea of testing a novel methodology to trigger flexibility provision, this being motivating customers to change their consumption patterns in response to variable DuoS tariffs so that the DSO achieves optimal DERs operation. It became evident from the beginning that an improved knowledge of the grid conditions would greatly contribute to the success of this methodology (i.e. flexibility provision via variable DUoS tariffs). However, currently in the Greek distribution network, the available real-time measurements are limited to those gathered by Supervisory Control and Data Acquisition (SCADA) system at the HV/MV substations, with the downstream part being mostly unmonitored since only MV customers are supported by telemetry (Automatic Meter Reading – AMR – service). This highlighted the need for developing a solution that would exploit the limited available data in a smart way to provide advanced grid observability. The SE tool is capable of providing the necessary input for designing flexibility provision services but can also remain as a valuable grid monitoring asset for the DSO.

The SE tool is executed every 15 minutes; it exploits the measurements obtained from the pre-existing metering infrastructure (SCADA, AMR) and the newly installed Synchronized Measurement Units (SMUs[1]) in order to deliver estimates of the power injections (P, Q) and voltages (magnitude and phase) of all network nodes of the Greek pilot site. Importantly, pseudo-measurements for unmeasured nodes are used in order to ensure the observability of the Greek pilot site and, thus, the solvability of the SE task. The achievement of complete grid observability and the availability of reliable estimates of its operating states allow the DSO to use ancillary services through the Platone Open Framework, which integrates various functions and services into a single and easy to deploy and use interface. Specifically for the Greek demo, the SE tool provides the necessary input for the design of the variable DUoS tariffs These tariffs are used as a method to leverage flexibility services and control DERs.

[1] SMU is the umbrella term for the device installed in the Greek demo, which can be flexibly configured to work as a waveform measurement unit, power quality analyzer, and PMU depending on the specific applications. In the Greek demo, the SMU units provided by RWTH were configured to work as PMUs. In the present document the terms PMU and SMU are being used interchangeably.

2.2.2 Overview of the validation framework

Figure 3 depicts the end-to-end Greek demo validation framework proposed by NTUA and HEDNO for the Platone demonstration. In this framework, the current field conditions are simulated in detail. More specifically, the DSO, with limited knowledge of the distribution network's full state, employs a Distribution State Estimation algorithm to obtain an estimated state, on which tariff design (utilizing simple tariff patterns) and tariff application are performed. For the Distributed State Estimation and DUoS tariff design solutions, a detailed quantification of their performance was built. As shown in Figure 3, results of the proposed method are compared with an ideal but unattainable scenario, where the DSO has perfect knowledge of the network state and directly controls all resources.

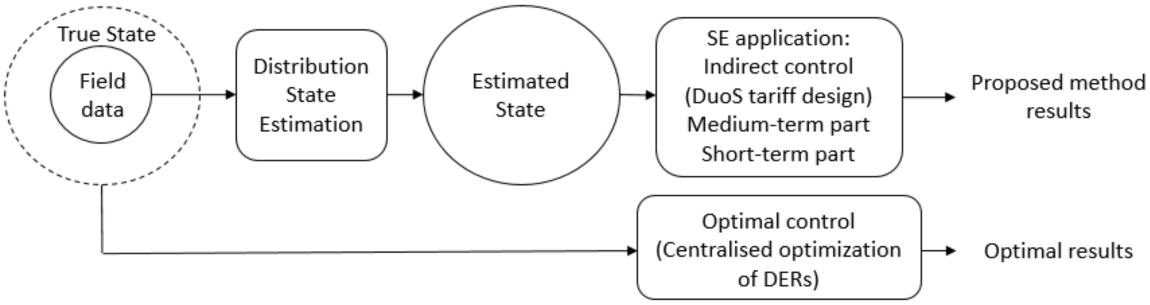


Figure 3: Overview of the methodology.

It is important to note that due to the absence of regulatory sandboxes in Greece for testing such concepts, end-to-end implementation and examination of the Greek solution could only be achieved through the detailed validation framework that was built. It is worth highlighting that all actors and entities that participate in the UCs defined for the validation of the proposed framework within the Greek Demo, including the DSO, TSO, aggregators, prosumers, and grid customers, were designed and modelled based on actual historical data. As it is common practice in similar studies, in order to test the efficacy of the algorithm for optimal DER control in enabling flexibility, the occurrence of additional network congestions was projected.

2.2.3 Dedicated hardware

The proposed model, as outlined in the validation framework and subsection 2.2.2, required significant computational resources. To address this, dedicated hardware was acquired for NTUA under the Platone project. As a result, the final model was efficiently solved and optimized on a 16-core 3.2 GHz Intel® Core™ i9-12900K processor with 64 GB of RAM. This hardware configuration enabled the successful execution of the complex computations involved in the model's analysis and will remain as a valuable asset for future research projects.

2.3 Demo Objectives

The objectives of the Greek demo were originally defined at the start of the Platone project in D2.1 [13] and D4.1, and later on, they were revised during the project's implementation. Thus, the objectives that were established throughout the project's duration are the following:

- Testing the Platone architecture and exploring its benefits for the Greek DSO (HEDNO).
- Installing PMUs in selected nodes of the Greek demo LV grid. The selection was made by the use of specific optimization techniques of the SE tool to facilitate the best possible performance of the algorithm.
- Testing the operation of the PMUs in adverse weather conditions, specifically extreme heat during summer months, to improve the device's Technology Readiness Level (TRL).
- Improving grid operation through advanced grid observability achieved by the installation of novel PMUs and utilizing their measurements in an SE tool.
- Achieving optimal dispatching, addressing local congestion and voltage level issues using novel approaches for flexibility mechanisms at DSO level. This includes utilizing variable DUoS tariffs to mobilize DER flexibility while ensuring cost recovery for DSOs.

- Coordinating DERs to provide ancillary services, such as frequency support, to the TSO by using close to real time DUoS tariff augmentation that accounts for frequency support requests.
- Adapting the Platone Open Framework for the Greek demo context and deploying Platone DSOTP and Blockchain Access Platform (BAP) on premises.
- Assessing the penetration limits of DERs for better control and planning of the distribution network.

As the Platone project reaches its conclusion, the Greek demo has successfully achieved its objectives, overcoming various obstacles encountered in the process. Through the successful accomplishment of these objectives, the Greek demo has showcased the effectiveness and potential of the Platone Open Framework in advancing grid operations and optimizing the integration of DERs within the distribution network. The results of the Greek demo further emphasize the importance of harnessing the available flexibility, especially in light of the increasing demand needs and installed Renewable Energy Sources (RES) capacity anticipated in the upcoming years [14].

3 Platone Open Framework implemented in Greek Demo

In the rapidly evolving landscape of electricity distribution networks, ensuring efficient and reliable operation requires robust equipment and infrastructure that can adapt to the increasing complexity of the grid. The Platone Open Framework aims to enhance the management capabilities of DSOs, and to achieve this, multiple components had to be integrated through a collaborative effort.

Figure 4 illustrates a high-level architecture of the Greek demo, showcasing the various tools and services that were essential for the successful implementation of the Platone project. The scope of this chapter is to present a clear overview of both the pre-existing and newly developed equipment and infrastructure in the context of the Greek demo.

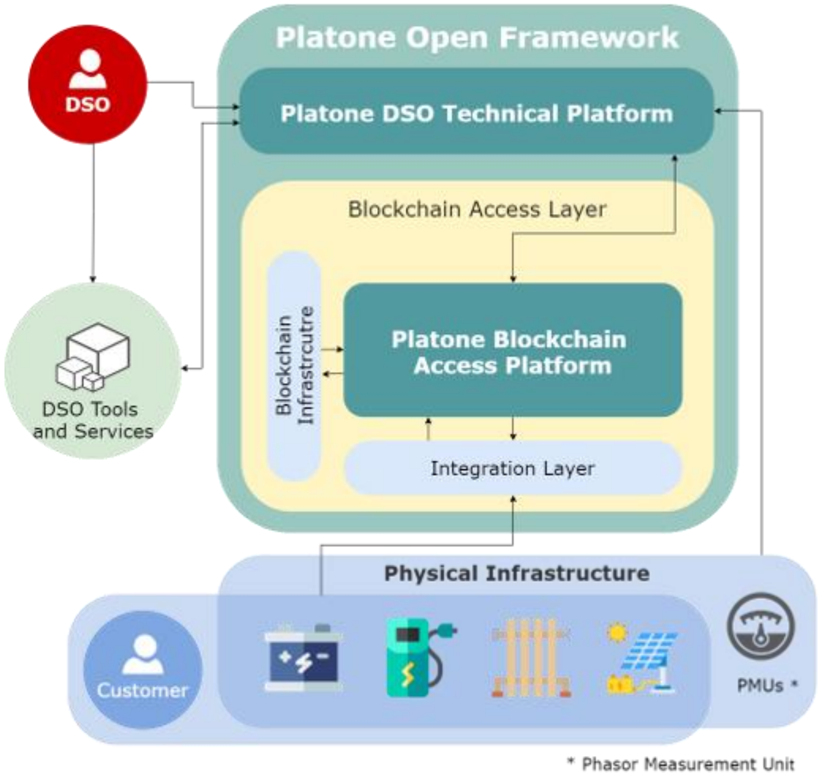


Figure 4: Greek Demo Architecture.

The Platone solution consists of a two-layer architecture named Platone Open Framework; a modular and configurable solution that can be adapted to the needs of the DSOs. This Framework, whose requirements and reference architecture are thoroughly described in D2.1 and D2.2, consists of three platforms developed by WP2:

Platone Blockchain Access Layer (BAL): a blockchain-based solution that includes two different components: the Platone Blockchain Access Platform (BAP), which allows the integration of the data coming from the physical infrastructure adding a level of security, transparency and trustworthiness thanks to the blockchain technology and smart contracts, and the Platone Shared Customer Database (SCD), which contains all the energy data (e.g., measurements, set points, etc.), provides authorized stakeholders with access to these data and implements data security, data privacy and data access policies mechanisms.

Platone Market Platform (MP): designed to support wide geographical area flexibility requests from TSOs and local flexibility requests from DSOs. Aggregators' offers are matched with these requests and conflicts are resolved in accordance with predetermined dispatching priority rules. All the market operations are registered and certified within the blockchain service layer, ensuring transparency, security and trustworthiness among all the market participants.

Platone DSO Technical Platform (DSOTP): a secure and efficient solution that enables DSOs to manage their grid effectively. DSOTP is based on an open-source extensible microservices platform, where

DSOs can deploy specific services as Docker containers and execute them on Kubernetes. The Data Bus layer, included on the DSO Technical Platform, allows for the integration of other components of the Platone Open Framework, as well as external tools and services, providing a direct connection to the DSO's classical SCADA system through standard communication protocols.

In the context of the Greek demo, a specific configuration which includes the BAL and the DSOTP was chosen; the BAL that validates the data coming from all the Physical Infrastructures and the DSOTP that runs all the tools and services needed to provide better control over the DSO's network. The Greek demo architecture is provided in Figure 5.

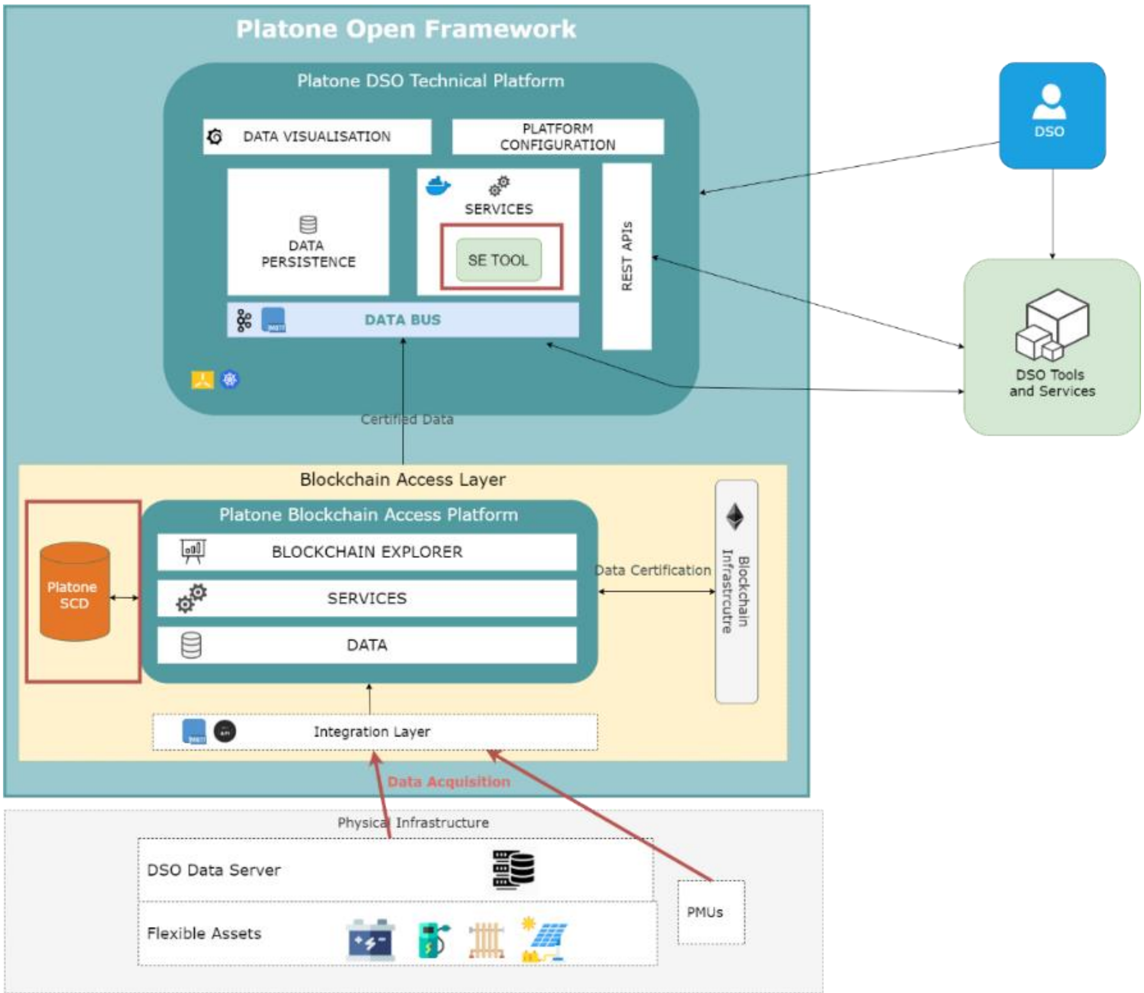


Figure 5: Greek Demo Architecture in detail.

The integration of the Platone Open Framework for the Greek demo took place in three phases. First, the BAL was deployed on HEDNO premises and the DSO Data Server in M28 (December 2021). Then, the PMUs were installed on the field during M43-M46 (March 2023 through June 2023) due to the delay of the current and voltage sensors procurement. Finally, the DSOTP deployment that includes the demo-specific tools went on through M45-M47 (May 2023 through July 2023) with the support of RWTH. The progress of the last two phases of the Platone Open Framework implementation can be seen in Figure 6.

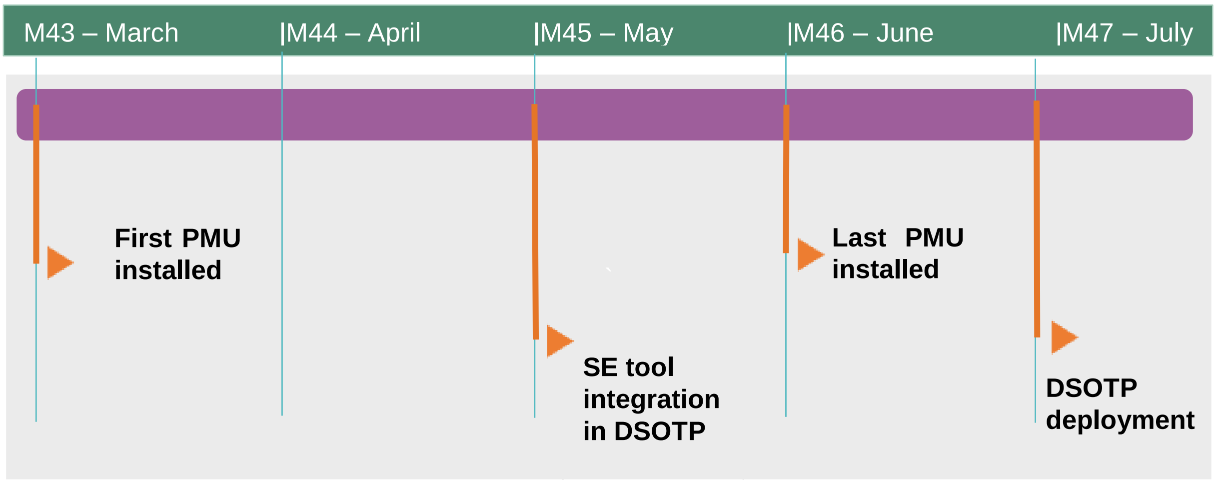


Figure 6: Timeline of the second and third phase of Platone Open Framework integration.

Within this chapter, two key facets are explored: existing equipment and infrastructure, and new software and hardware solutions developed within the Platone project. The former encompasses established systems that have played a pivotal role in managing distribution networks, while the latter introduces cutting-edge innovations developed as part of the Platone project.

Subchapter 3.1 focuses on the existing equipment and infrastructure which includes the systems of the Greek DSO that were incorporated in the Platone solution and were already in use by HEDNO before the Platone project. These are the Supervisory Control and Data Acquisition – Distribution Management System (SCADA-DMS), the AMR system, the Geographic Information System (GIS) and the DSO Data Server.

Subsequently, subchapter 3.2 explores the newly developed software and hardware, which comprise of the platforms, the algorithms, and the advanced metering systems developed specifically for the Platone project. Firstly, the software-related aspects are presented, including the BAL, the DSOTP, the SE tool, the algorithm for optimal DER control, and the algorithm for ancillary services. Then, a brief description of the novel PMU developed by RWTH is presented.

3.1 Existing equipment and infrastructure

This section provides a brief description of the existing systems and infrastructure utilized specifically for the Greek demo within the proposed Platone Open Framework solution. For each one of the metering devices, the type of measurements provided is also presented.

3.1.1 Supervisory Control and Data Acquisition – Distribution Management System (SCADA-DMS)

This is a core system for HEDNO’s day to day operation as the Greek DSO. The services provided by HEDNO’s SCADA-DMS include among others:

- Alarm management
- Topology information (with feeder traces and schematics)
- Fault management
- Power flow analysis
- Outage management
- Monitoring and extraction of quality indices
- Load shedding
- Asset management
- Short-circuit analysis
- A virtual environment that simulates real grids, used as a study environment for investigating distribution feeder optimization, protection coordination and operator training simulations.

Regarding the type of measurements provided by the SCADA-DMS system, the voltage magnitude at the HV/MV substation, identified with the slack bus of the network presented in subchapter 2.1, is provided. Additionally, the system also provides information on active/reactive power flows and current magnitudes at the top of the distribution feeders.

3.1.2 Automatic Meter Reading (AMR)

Smart meters are installed in all MV customers and are currently being installed in the largest LV customers as well. Through the help of AMR, the distributed energy is monitored by establishing communication with the smart meters and retrieving time series data once every 24 hours. Specifically, the AMR system provides information on the active and reactive power injections – loads and generations – from MV customers. The smart meters collect their readings at 15-minute intervals.

3.1.3 Geographic Information System (GIS)

The GIS, designed to collect, analyze, manage and depict spatial and geographical network data, is a flexible system that can collaborate with other systems and technologies related to network operation and management, such as SCADA-DMS. Operators can monitor the network status in real-time, which enhances the operational efficiency. Therefore, GIS serves as a valuable tool for grid planning, optimization, and maintenance strategies. As part of the rollout of the system in the Greek Distribution Network, the Mesogeia region, which includes the Greek demo site, and West Thessaloniki were the first regions to be equipped with a GIS. The Mesogeia GIS pilot commenced in April 2017.

3.1.4 DSO Data Server

The DSO Data Server, operated by HEDNO, is a dockerized database that hosts DSO data. This includes network data as well as AMR data for both MV and LV customers. The primary purpose of the DSO Data Server is to facilitate data analytics and research activities.

3.2 Platforms – Tools and Services – Advanced metering systems

The following section presents a concise overview of the components developed within the scope of the Platone project, both software and hardware components. The description begins with the software components that constitute the Platone Open Framework, as implemented in the Greek demo. Subsequently, the hardware component, which is the novel low-cost PMU developed by RWTH, is described.

For a comprehensive understanding of the tools and algorithms developed for the Greek demo by NTUA, detailed information can be found in D4.2, D4.3 and D4.4. Regarding the description of the platforms utilized in the Greek demo, developed by ENG and RWTH, further and more specific information can be found in D2.8 and D2.13. Hence, in this subchapter, each section provides a brief overview of the main concept behind each component while focusing primarily on the modifications made in relation to the aforementioned Deliverables.

3.2.1 Blockchain Access Layer (BAL)

The Platone BAL is developed by WP2, and it is installed in HEDNO premises. This layer includes two main components:

- **Platone Blockchain Access Platform (BAP):** utilizes blockchain technology through smart contracts and offers an interface for the integration of the data coming from the physical infrastructure.
- **Platone Shared Customer Database (SCD):** it comprises of all the measurements, set points and other necessary data collected from customer's physical infrastructure. It provides easy access to data for other components and stakeholders of the Platone Open Framework while ensuring security and privacy are not compromised.

The second and final version of BAL architecture is depicted in Figure 7.

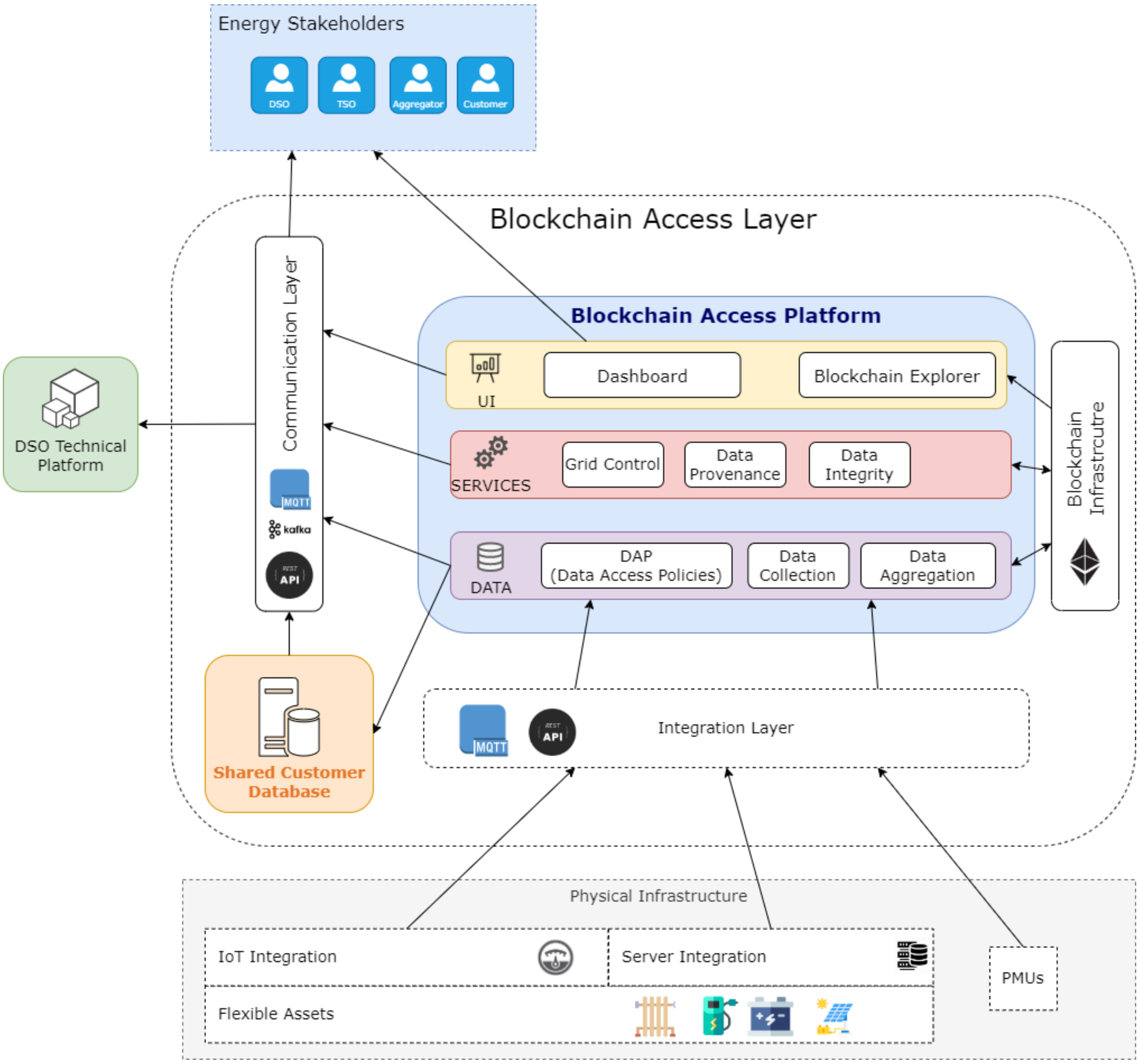


Figure 7: BAL architecture (v2).

As described in D2.15 [15], the BAL includes a Message Queue Telemetry Transport (MQTT) broker server, based on Mosquitto, allowing the integration of data coming from PMUs, metering devices and Data Servers. It also takes care of defining authentication and authorization mechanisms that allow to uniquely identify the data owner. Finally, it allows to publish data with high frequency without placing any restrictions on the data format.

The Business Layer of the BAL is, among other things, capable of managing specific data format and data models. In this second prototype, JSON and Extensible Markup Language (XML) are allowed as data format and the following data models were integrated and supported:

- PMU Data Model
- Measurement (CIM IEC 61968-9)
- Grid Topology (CIM IEC 61970-X)

In the integration scenario for the Greek Demo, the DSO can decide how to publish data (e.g., DSO Data Server and/or PMU data) and how their own data can be available for the external system and stakeholders (e.g., the DSOTP). The BAL implements a set of configurable rules for the data access, including permission and security mechanisms. Figure 8 represents the updated integration schema of the Platone BAL. As expected, there have been demo-specific configurations of BAL so that the platform meets each demo’s needs. For example, in the Greek demo the PMU data are provided in XML format due to the data converter presented in subsection 3.2.3, which was built to handle the necessary data formatting for the SE tool.

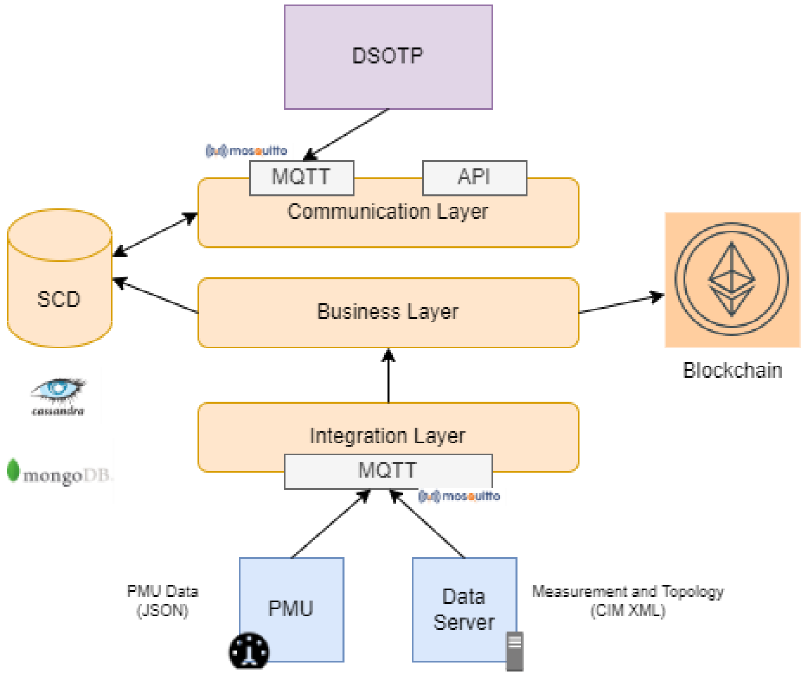


Figure 8: BAL integration schema [15].

The deployment of the BAL in HEDNO premises was carried out through M28 with the cooperation of ENG partners and HEDNO IT Department. A dedicated server is utilized for the deployment and management of the Docker containers through Kubernetes.

3.2.2 Distribution System Operator Technical Platform (DSOTP)

The Platone DSOTP, a core component of the Platone Open Framework, is based on previous work done in the Horizon 2020 project SOGNO [16] and relies on a micro-service architecture. The key idea is the decoupling of all different functionalities into individual micro-services to ensure modularity of different services and core infrastructure components of the platform.

All services running on the DSOTP are deployed on Kubernetes [17] clusters. For this reason, the containerization of each micro-service through Docker [18] containers is required. In this way, high availability, scalability and modularity of the services are ensured. Regarding the Greek demo, grid observability was enhanced through the SE tool that was dockerized and ran in Kubernetes in a Virtual Machine (VM) that was set up on HEDNO premises.

Figure 9 illustrates the architecture of the DSOTP [7]. The Databus is implemented by means of a message broker (MQTT) to which all services can publish and subscribe in order to exchange data. This exchange can happen both internally between micro-services and externally with field devices and other platforms or legacy systems.

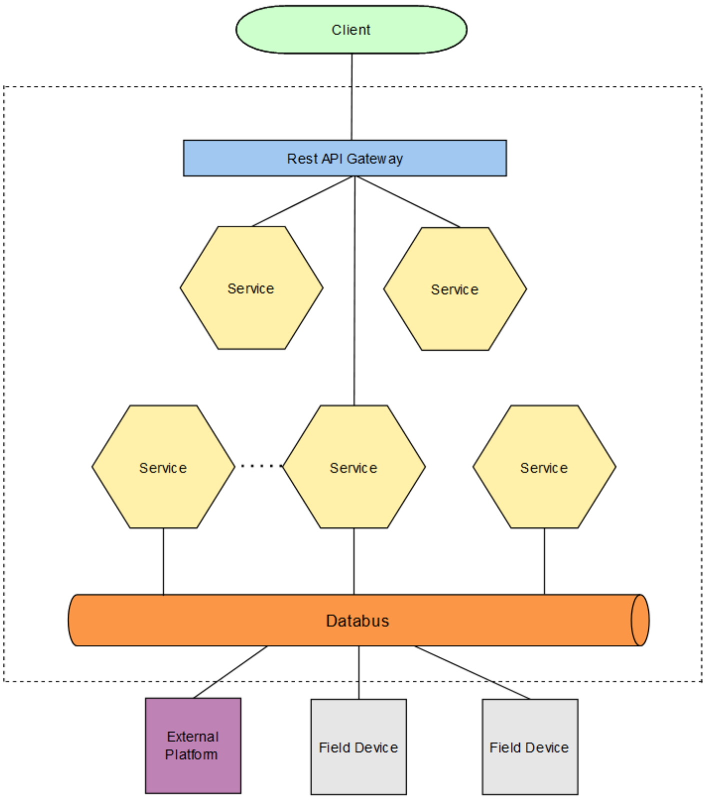


Figure 9: DSOTP architecture [7].

The SE tool integrated in the DSOTP

The SE tool, which is presented in the following section 3.2.3, is the service added as part of the DSOTP of the Greek demo. For this to happen, the transition of the SE tool code from Matlab to Octave was necessary in order to tackle the problem of Matlab licensing. SE is able to run receiving joined information from the SCADA, AMR and PMUs via the Databus.

Furthermore, a graph representation of the network is generated in a Dashboard utilizing the information from the Common Information Model (CIM) data and the lines P210 and P490. Originally, a static graph layout was created with the help of NetworkX package [19] to parse the XML files. This layout was imported into a custom react app using react-flow [20]. Thus, an interactive network display can feature the results of the SE on the network of the Greek demo with the values of Voltages (amplitude and phase) and Powers (active and reactive) being calculated for each node, every 15 minutes.

In Figure 10 the deployment structure of the SE tool is presented. The components added during the final integration of the DSOTP in the Greek demo can be seen in green boxes, while the already existing components of the DSOTP are shown in yellow boxes.

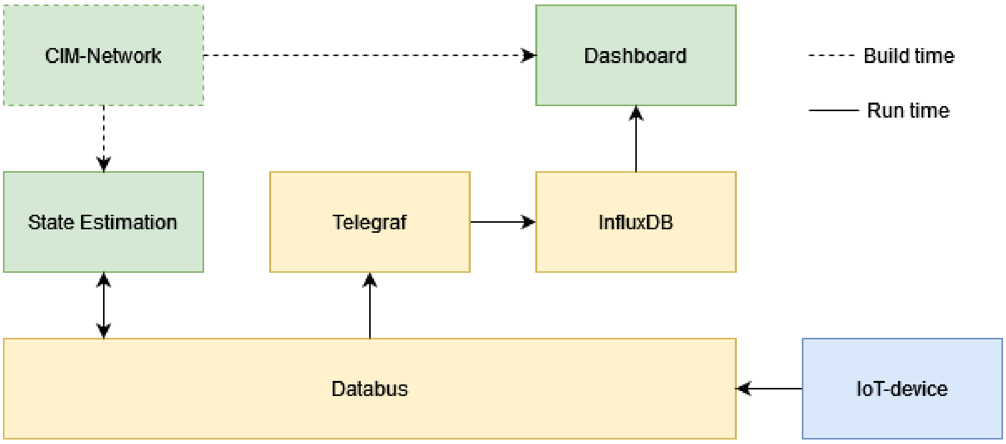


Figure 10: Deployment structure of the SE tool [7].

3.2.3 State Estimation tool

The SE tool, which is detailed in D4.2, is a distribution system state estimator developed by NTUA for the monitoring of the Mesogeia pilot site and the support of the algorithm for optimal DER control. The SE tool processes the available measurement data in order to estimate the nodal complex voltages of the grid and, thus, to capture its operating state. As elaborated in D4.2, it is based on the Weighted Least Squares (WLS) method and can process conventional and synchronized measurements.

As regards the deployment of the SE tool, the measurement set comprises:

- conventional actual data from the SCADA system at the HV/MV substation of Nea Makri (from which the 2 feeders of the pilot site originate) and the power meters installed at MV consumers and PV units as well as pseudo-measurements via a load allocation scheme for MV/LV transformers,
- synchronized actual data from the 5 SMUs installed at MV/LV transformers.

The external tool for the generation of pseudo-measurements for the MV consumers and the PVs (short term load forecasting) was not utilized in the demonstration phase, since HEDNO provided the actual near real-time measurement data in the form of time series from the measurements of the SCADA, AMR and PMUs that have been previously described. In case no real-time data are available (e.g. loss of communication between the meter and the logging software running on HEDNO's central server), the SE tool can utilize time-delayed data, e.g. data provided with a latency after certification. Additionally, it is noteworthy that the full framework of the SE tool in cooperation with the external tool was used to produce the training data for the algorithm for optimal DER control.

The overall setup of the SE tool as deployed in the HEDNO DSOTP is demonstrated in Figure 11.

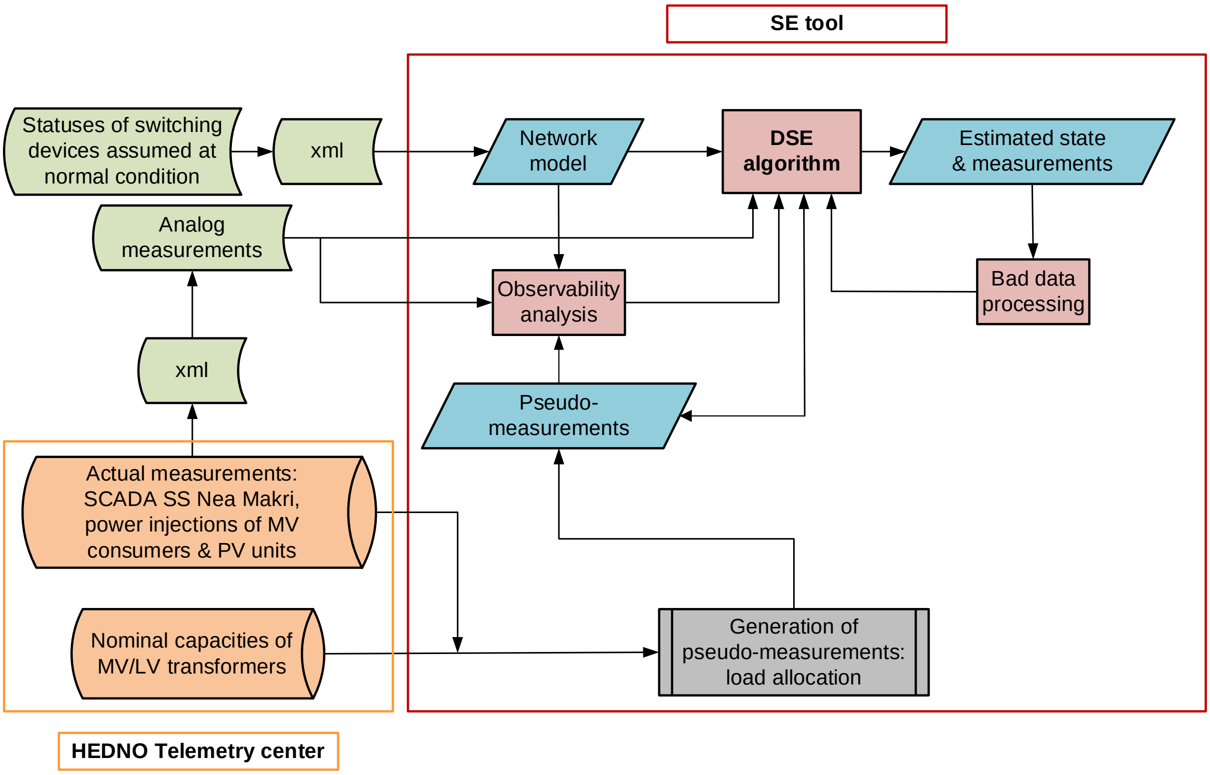


Figure 11: Overall setup of the SE tool as deployed in the HEDNO DSOTP.

As part of the implementation of the SE tool in the Greek Demo, the development of data converters was required. In particular, the network model (topology) of the Greek demo site, as well as the actual measurements are originally stored in form of the XML format according to the CIM standard. However, the SE tool can receive input files stored in the well-established Power System Simulator for Engineering (PSS/E) power flow data format. Therefore, for the data required by the SE tool to be readable, intermediate converters are employed to rearrange them in the PSS/E file format according to the requirements of the SE tool.

The data fed into the SE tool are classified into two types which are processed by the network and the measurement converters, respectively. The first data type refers to the topology of the 2 feeders comprising the Greek demo, i.e., the characteristics of their nodes (e.g., load/ generation, nominal capacity) and their lines (e.g., complex impedance) as well as their configuration. The second data type pertains to the measurements, which are provided from various network assets in real time (SCADA, AMR and SMU). Figure 12 presents the dataflow for the overall operation framework including the data converters and the SE tool. The converters have been developed in Python programming languages. More information about the data converter are provided in Annex A.

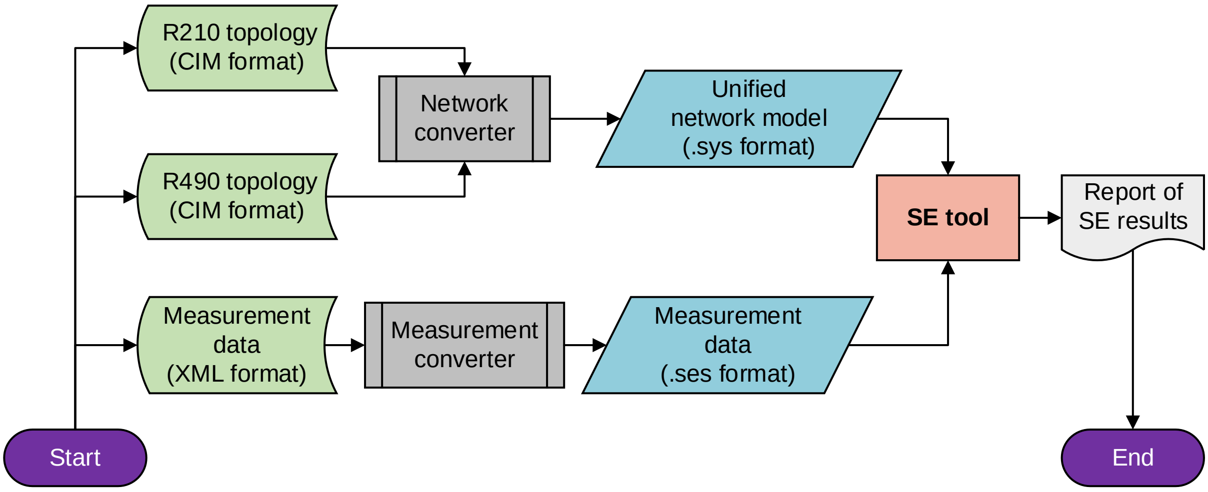


Figure 12: Dataflow of the overall operation of the SE tool.

3.2.4 Algorithm for optimal DER control

3.2.4.1 Methodology

This algorithm is extensively described in D4.4 and refers to the framework methodology and tool developed by NTUA for the optimal control of DERs. The main idea behind this methodology is the calculation and implementation of variable DUoS tariffs to mobilize DER flexibility, while retaining the traits of the traditional DUoS tariffs, such as DSO cost recovery through tariff revenue and simplicity for the end-user. Under the traditional DUoS tariffs regulatory frameworks, the value of the DUoS is based mainly on long-term cost recovery considerations. The algorithm for optimal DER control envisages to design DUoS tariffs on an annual basis, but deciding the actual value of them based on the short-term grid conditions enabling better exploitation of the inherent flexibility of DERs, leading to increased economic efficiency in the operation of the distribution network.

The overall DUoS tariffs design setup, which takes place annually, and the validation setup, which refers to the daily operation, can be seen in Figure 13 [21].

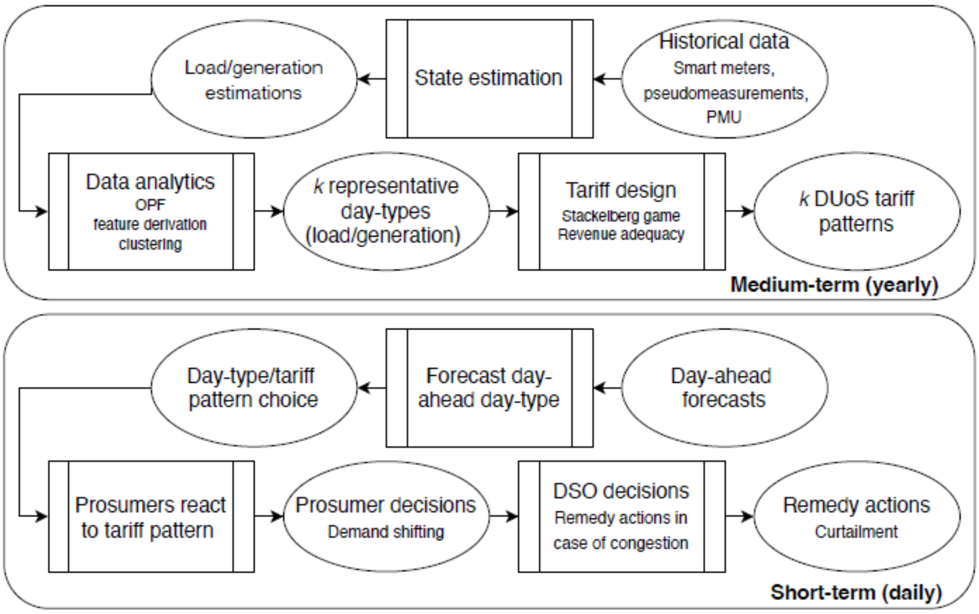


Figure 13: Design (medium-term) and implementation (short-term) setups of the proposed DER control framework [21].

The method employed to design the variable DUoS tariffs utilizes a bilevel optimization mathematical model, specifically a Stackelberg game formulation, which effectively captures interactions between the DSO (upper level) and the prosumers with DER (lower lever) [22]. Regarding the upper level of the optimization model, the objective of the DSO is to minimize the operational costs while complying with the power flow constraints, the tariff format constraints, and the revenue recovery constraints. On the lower level, the prosumer aims to minimize costs and discomfort, while respecting the DER constraints. This model, as formulated, cannot be solved directly, and therefore, it is transformed into a Mathematical Problem with Equivalent Constraints through Karush-Kuhn-Tucker (KKT) conditions of the lower level added as constraints to the upper level. This new model is then linearized and becomes a Mixed-Integer Quadratically constrained Program.

Additionally, this methodology considers a detailed representation of the power flow constraints, different levels of temporal and spatial granularity in the designed tariffs, as well as discrete tariff levels to ensure intelligibility. Finally, it is important to note that the tariffs are designed annually using historical data. Implementing a clustering approach based on K-means with weighted average, variable tariffs are designed to adapt to the forecasted conditions of the upcoming day. In the following subsection, the validation setup is presented along with the results and the conclusions drawn from different scenarios.

3.2.4.2 Results

The validation setup for this methodology is illustrated in Figure 14 and comprises two phases: the design phase, which generates the DUoS tariff patterns for the entire year, and the validation phase, where three distinct cases are tested on actual network conditions during daily operation. The first case of the validation phase, known as the Business-as-Usual (BaU) scenario, employs flat tariffs that demonstrate 0% efficiency since they cannot motivate any flexibility. The second case applies the proposed framework where the DERs are indirectly controlled via the variable DUoS tariffs derived from the design phase. The third case refers to the theoretical optimal scenario where the DSO directly controls all available flexibility and has perfect knowledge (100% efficiency).

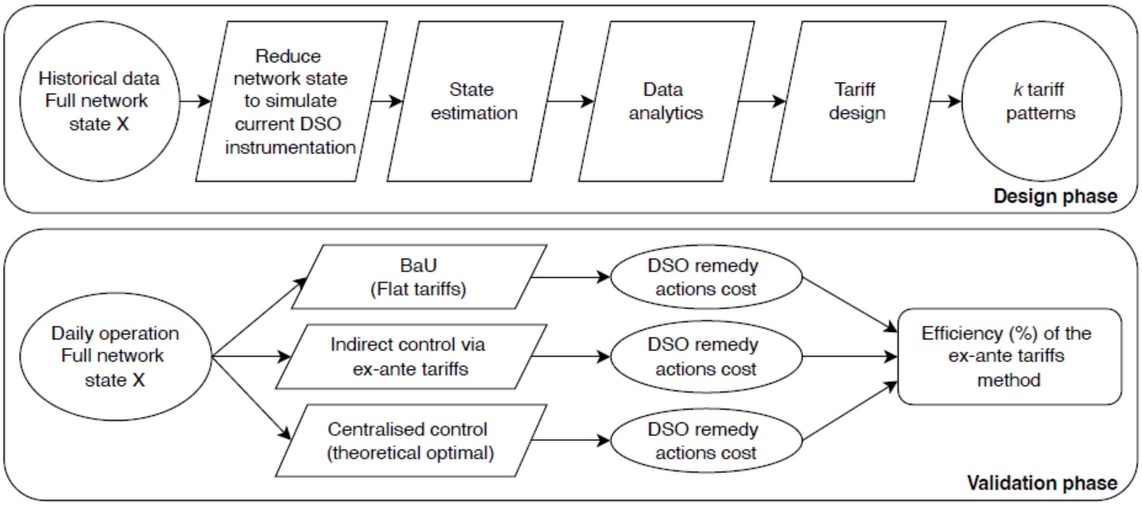


Figure 14: Overview of the validation setup [21].

It is also important to note that for the validation framework employed to test the algorithm for optimal DER control, a portion of the R210 feeder of the Mesogeia pilot site was used, as depicted in Figure 15. As previously mentioned in section 2.2, all the entities involved in the framework (e.g., prosumers, DSO etc.) are also simulated. As it is common practice in similar studies, to effectively assess the algorithm's performance, an additional assumption needed to be made; the introduction of extra loads that resulted in line congestions, requiring curtailment actions by the DSO and subsequently the need for mitigation measures.

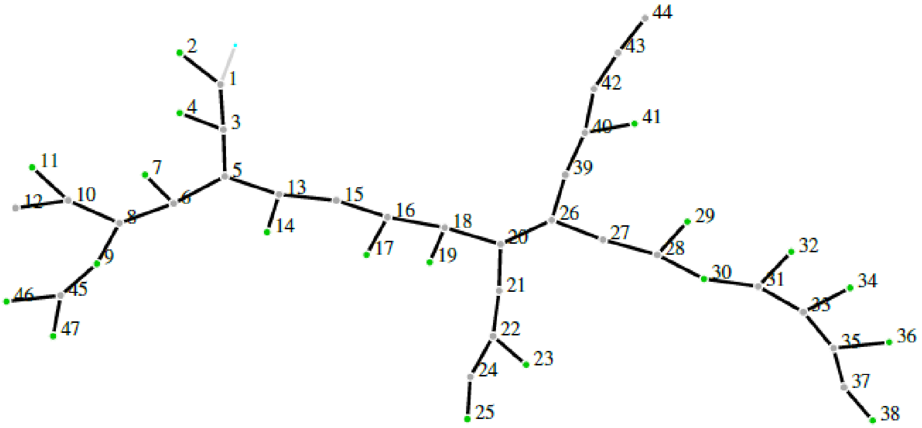


Figure 15: Test network: active prosumers at 2, 23, 25 and PV at 29, 32, 34, 36, 38

Regarding the design phase, the DSO can select hyper-parameters such as the number of day-types, k, for which DUoS tariffs are designed, and the demand shifting limit, a_i, for flexible prosumers. The presented results are for $k = 4$ and $a_i = 20\%$, which is a good compromise between simplicity and effectiveness in cost reduction. Regarding the clustering of the 4 different day-types, the clustering module (weighted k-means) gives that each day-type has a weight of 60, 19, 98 and 150, respectively. Indicatively, Figure 16 illustrates the curtailment decisions of the model under the BaU case of the Flat tariff. One can notice that, the most problematic day-type is day-type 2, which corresponds to 14 days only. The most common day-type is number 4 for which no issues are observed. Day-types 1 and 3 correspond to solely demand and generation related problems, respectively.

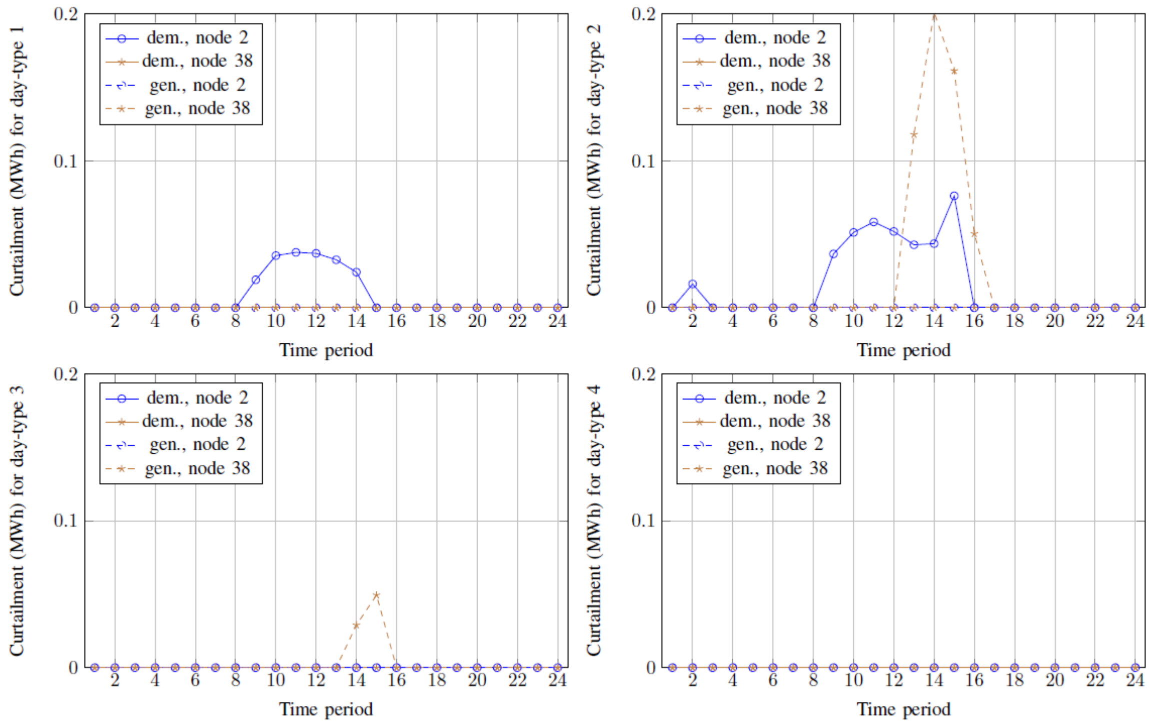


Figure 16: Demand (dem.) and generation (gen.) curtailment under the flat tariff case [21].

A summary of the different day-types characteristics can be seen in Table 2Table 2.

Table 2: Day-type characteristics.

Day-type	Generation	Demand	Congestions

Day-type 1	Normal	High	Many
Day-type 2	High	High	Many
Day-type 3	High	Normal	Many
Day-type 4	Normal	Normal	Few

Figure 17 and Figure 18 showcase the optimal network tariffs for three nodes of the test network under the hourly (temporal granularity only) and hourly-loc (full temporal and spatial granularity) schemes, respectively. The flat scheme is 20 €/MWh for all nodes, hours and day-types which is the current DUoS tariff scheme in Greece and it is not shown in a separate figure for simplicity. The proposed model was implemented in Julia [23], utilizing the JuMP package [24] and solved using the optimization software Gurobi [25].

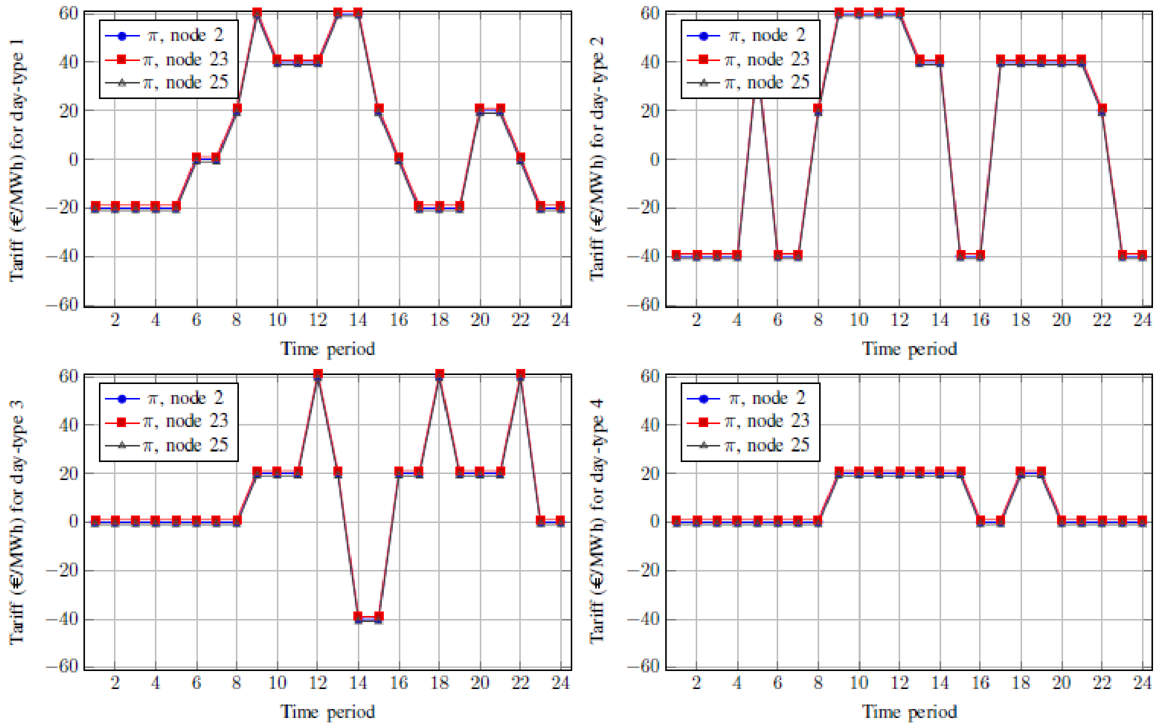


Figure 17: Hourly network tariffs at active prosumers nodes [21].

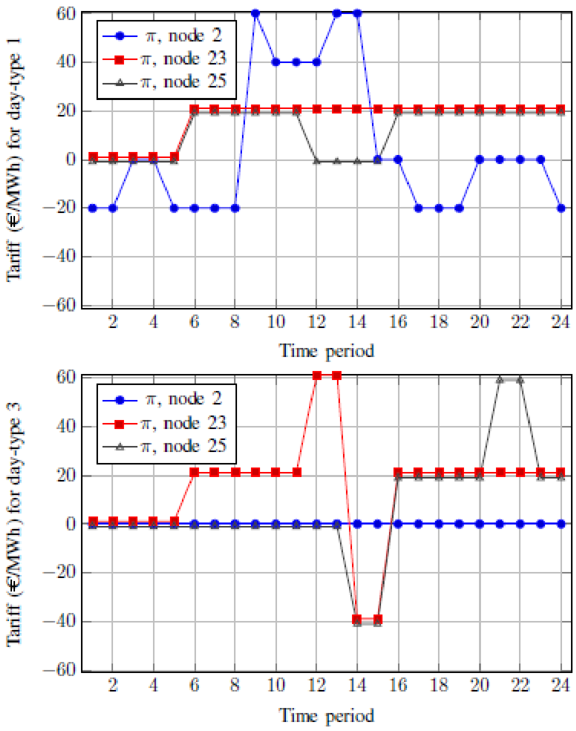


Figure 18: Hourly-loc network tariffs at active prosumers nodes [21].

Furthermore, the out-of-sample validation scenario examines tariff efficiency under realistic conditions for a full-year sample. Table 3 presents demand, generation and total curtailment costs in €, as well as the number of violations for $k = 4$ clusters. Additionally, the table includes benchmark results obtained from perfect coordination determined by the centralized Optimal Power Flow (OPF) approach, representing the theoretical optimal.

Table 3: Out-of-sample curtailment costs (in €) and k=4 number of violations for k=4 clusters.

Scheme	**Curtailment costs and number of violations**			
	Demand curtailment cost	Generation curtailment cost	Total cost	Number of violations
Flat	2552.6	2850.2	5402.8	948
Hourly	1016.6	2763	3779.6	779
Hourly-loc	806	2687.5	3493.5	733
Optimal	248.3	2251	2499.3	367

Conclusions regarding the algorithm's efficiency were drawn based on numerous out-of-sample simulations across different cases. The results indicate that the efficiency of the algorithm in resolving problematic grid conditions increases with higher temporal and spatial granularity of the DUoS tariffs. As it can be seen in Table 3 the number of violations decreased significantly in the 'Hourly' scenario (temporal granularity) compared to the traditional flat DUoS tariff, and it decreased even more in the 'Hourly-loc' scenario (temporal and spatial granularity). Another observation is that the decrease of violation costs is mainly originating from demand curtailment costs. The reason behind this, is that the demand curtailment penalty is much higher than the generation curtailment penalty and therefore, in the optimal solution demand curtailment reduction is always prioritised over generation curtailment. If a different (higher) generation curtailment penalty was preferred, then generation curtailment occurrences reduction (%) would be also higher. Moreover, an increased number of clusters regarding the day-types leads to improved efficiency, but in the case of the Greek demo even with only 4 tariff patterns for the entire year, the designed tariffs capture nearly 80% of the potential efficiency as can be seen in the results presented in D4.4 [3]. Therefore, variable DUoS tariffs can effectively unlock most of the available DER flexibility in distribution networks, and a small number of tariff patterns can capture a substantial portion of the efficiency improvement.

3.2.5 Algorithm for ancillary services

3.2.5.1 Methodology

This algorithm is extensively described in D4.3 and refers to the framework methodology and tool developed by NTUA for the coordination of DERs in order to enable them to provide ancillary services to the TSO upon request. The proposed framework described in the last section for the design of ex-ante tariffs as specified in D4.4, is complemented by an analogous model for a close-to-real-time tariff design. Thus, the previously designed Day-Ahead (DA) DUoS tariffs design method was expanded to realize the method to design RT DUoS tariffs.

The DSO normally operates with the tariffs designed from the DA framework. Whenever the DSO receives a request from the TSO for balancing energy from DERs, the RT DUoS tariffs design method is executed. The DA tariffs are redefined based on a bilevel optimization mathematical model, specifically a Stackelberg game, where now the constraints are altered. The newly designed tariffs are implemented for the rest of the day and are communicated to all the involved parties (active prosumers) to mobilize their flexibility and change their consumption patterns.

The scope of the specific problem is not a year, as it was for the algorithm for optimal DER control, but the next operational time period and the rest of the day. Additionally, another difference with the design of the DA DUoS tariffs is that they are designed on the spot (real-time), upon a TSO request, and they are not scheduled to be designed before the start of each year. That is the reason that the day type is now not considered for this process and the revenue adequacy constraint is optional. Figure 13 still applies throughout the year, but for this case, also Figure 19 is considered in short-term, close to real-time context (in practice hour-ahead, although it can be shorter), after a TSO request to the DSO.

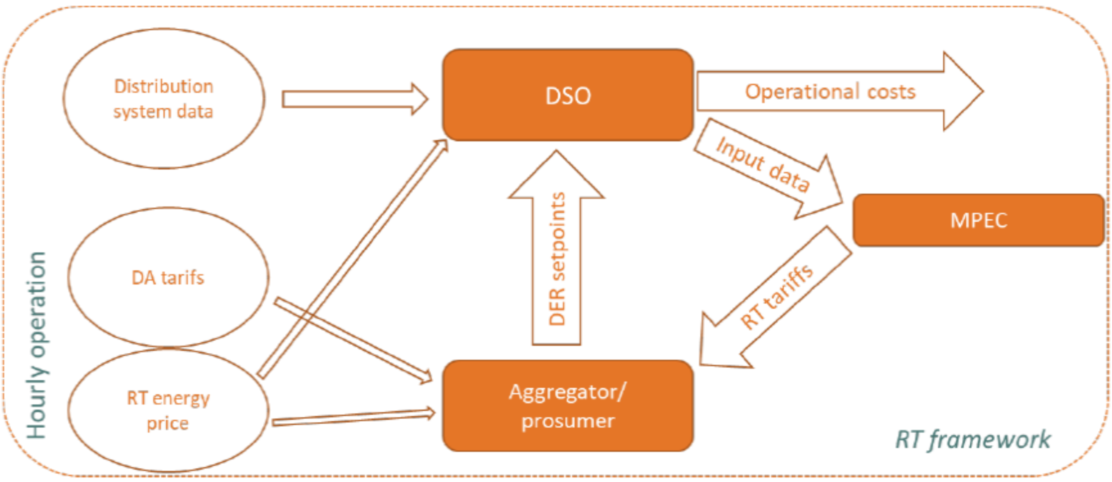


Figure 19: RT tariff utilisation framework.

It has to be specified that currently in Greece there is no use of variable DUoS tariffs, hence the TSO entity had to be simulated. Furthermore, no real instances for which the TSO has requested flexibility from the distribution network exist, because such a framework does not exist yet in many European countries, including Greece. So, as with the DA tariff method in 3.2.4, a design and validation framework were created to test the methodology and it is presented in the following section.

3.2.5.2 Results

The RT DUoS tariffs are applied complementary to the DA DUoS tariffs. Therefore, the validation setup for this methodology builds upon the one described in section 3.2.4 and depicted in Figure 14. The added tariff term is designed close to RT upon a request from the TSO for balancing energy from the DERs.

Whenever a TSO request is made to the DSO, the calculation of RT DUoS tariffs is performed for the remainder of the day. This approach is adopted to ensure that a single tariff for the hour of interest does not postpone network issues later in the same day. Additionally, this framework is demonstrated for simplicity only for the hourly-loc (full temporal and spatial granularity) scheme. The proposed model was implemented in Julia, utilizing the JuMP package and solved using the optimization software Gurobi.

The results obtained from the simulations conducted in D4.3 present a year-long analysis of the costs incurred with and without the proposed framework of the RT DUoS tariffs. Table 4 presents the aggregated operational costs per day-type and the total costs. A significant variation in the percentage-wise effectiveness of the method per day-type is observed that can be explained through the differentiations of the day-types. It is important to make clear that the results of the clustering are different for this case comparing to the ones mentioned in subsection 3.2.4.2, since different simulations were ran for the validation of the two distinct methodologies. Hence, day-type 1-4 characteristics that follow are not the same as the ones in Table 2.Day-type 1 is the most common day-type, where no network problems occur. Day-type 3 is a lightly congested day, where not all flexibility is used by the DA tariffs. Thus, there is volume available to be used for the problems that occur due to the TSO balancing request.

Day-type 4 is a very congested day-type. There are a lot of limit violations that require curtailment throughout the daily operation. In this case, the DA tariffs harness almost all of the available flexibility. The result is that, when the TSO request arrives, the RT tariffs can motivate little flexibility volume to address the additional issue. A similar problem occurs for day-type 2 days, which are the ones with mostly line congestion problems observed, due to excessive PV production, during summer days.

Table 4: Summary of the operational (curtailment) costs for different day-types throughout the year, without and with the use of RT network tariffs.

Operational costs (€)	Without RT tariffs **(€)**	With RT tariffs **(€)**	Decrease **(€)**	Decrease (%)
Day-type 1	905.74	121.2	784.5	86.61
Day-type 2	3468.95	2587.17	881.77	25.42
Day-type 3	1822.32	839.40	982.92	53.94
Day-type 4	6603.19	5981.60	621.59	9.41
Total	12800.20	9529.37	3270.78	25.55

The values in Table 4 represent a comparison of the operational costs resulting from the implementation of the DA DUoS tariffs scheme (namely without RT tariffs) and the RT DUoS tariffs scheme (namely with RT tariffs) proposed as an extension of the original model (DA DUoS tariffs only) presented in the previous section 3.2.4. The results are categorized per day-type, and the total decrease in operational costs is 25.55% based on the year-long analysis conducted in D4.3. Therefore, it can be concluded that the method of RT DUoS tariffs, when combined with the DA DUoS tariffs, demonstrates significant savings in operational costs. The RT DUoS tariffs effectively optimize the distribution network's operation, harnessing the benefits of real-time demand-response actions, resulting in significant cost reductions.

3.2.6 Phasor Measurement Units

PMUs from RWTH have been installed at the demonstration site in Mesogeia in order to provide phasor measurements in several network nodes to further improve applications such as SE. As part of the

Platone project, five PMU devices were installed in the Greek demonstration site. In its most recent development, phasor measurement service is provided by so-called SMU. From this point onward, the terms PMU and SMU will be used interchangeably in this Deliverable, since the SMU is an evolved version of the PMU.

In broader sense, SMU is a modular platform (Figure 20) that can provide different synchronized measurements. For the demonstration in Mesogeia, SMU functions as a low-cost PMU with costs for basic hardware equipment at around 200 EUR, and with open-source hardware design and software code [26]. SMU can provide phasor measurements with high reporting rate frequency, and it is compliant with phasor measurement accuracy standards. Some tests of the SMU hardware can be found in [27] and [28].

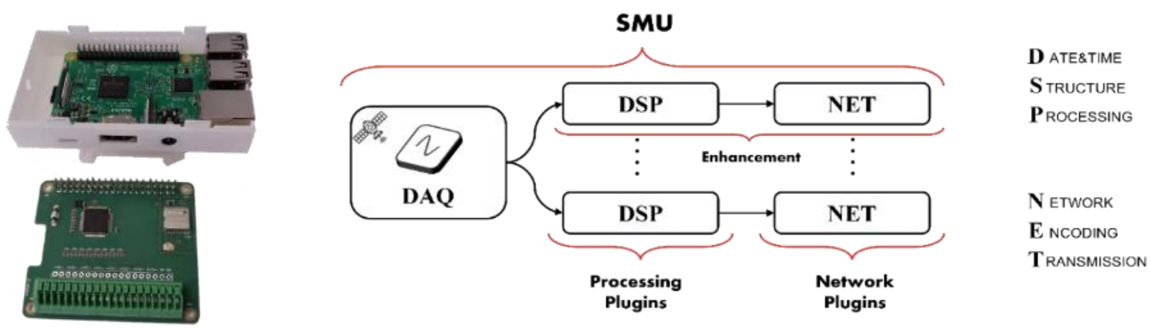


Figure 20: Modular structure of SMU with data acquisition board (DAQ), processing and network plugins.

For PMU functionality of SMU, which is used in the demonstration, phasor estimation algorithm IP-MSDFT (interpolated modulated sliding Discrete Fourier Transformation) was used, with its simplified structure presented in Figure 21.

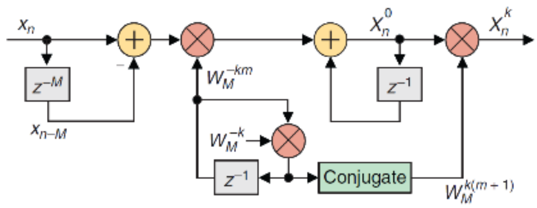


Figure 21: Flow diagram of the used phasor estimation algorithm.

Five SMUs are configured to monitor six channels with three phase voltages and three phase currents. The resulting phasors are further processed through a dedicated service that provides measurements in XML data format compliant with CIM, so that measurements get integrated further into the DSOTP and they become usable by the SE tool (Figure 22).

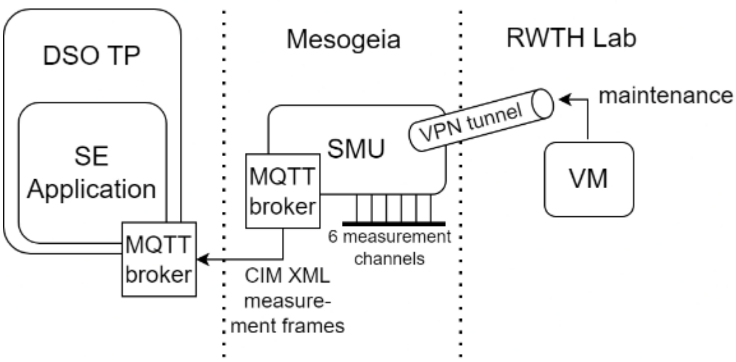


Figure 22: Connection of SMU in Mesogeia setup.

During the SMUs installation phase, RWTH provided support regarding their commissioning, including challenging tasks of current and voltage signals conversion and various integration aspects. To facilitate code maintenance and provision of additional services, the SMUs are connected to RWTH's virtual network. This connection allows for seamless collaboration between SMUs and other systems and provides access to necessary resources to support the commissioning and installation process.

3.2.6.1 Installation of PMUs in the distribution grid of the Greek Demo

The installation of the PMUs as part of the Greek Demo has a twofold function: using the data as input for the SE tool and investigating the robustness of the design against the extreme temperatures of the Greek summer.

The process of the installation consisted of the following stages:

1. High-level definition of connection requirements,
2. Communication and approval by the regional office of HEDNO to proceed with the installation,
3. Definition of sensors needed for signal acquisition and procurement,
4. Identification of the optimal nodes for installation,
5. Definition of the details of the installation (placement in the pillars, allocation of personnel etc.),
6. Procurement of materials needed and assembly of the PMUs, and
7. Final meetings and coordination with the regional office of HEDNO at Mesogeia and installation.

The effort to install the PMUs in the Greek Demo distribution grid commenced early in the project in 2020. The first step included the definition of the necessary voltage and current sensors, according to the technical standards and procedures that HEDNO follows. In discussions with the responsible Network Department, it was decided that the optimum placement of the PMUs would be on the LV side of the MV/LV substations (Figure 23). This option offered the following advantages:

1. The need for expensive MV voltage and current transformers was mitigated, and
2. The installation procedure would be less cumbersome, requiring minimal to zero disconnection time.

These benefits were concluded to be important enough to tolerate the error introduced in the measurements by the need to transform the voltage and current values to the primary (MV) of the transformer (transformation ratio 20/0,4 kV).

Figure 23: MV/LV substation in the area of Mesogeia.

Following that, the first meeting with representatives from the regional office of HEDNO in Mesogeia aimed at informing them about the concept of Platone and gaining the approval to proceed with the installation of the first version of the PMU. The size of that PMU (IP65 box, roughly 21x29cm) presented a challenge, in terms of fitting and mounting it in the pillar of the MV/LV substation, considering that space was needed for the voltage sensors as well. The space issue was dealt with by the arrival of the novel SMUs, as mentioned in the previous section, which are comparable to the size of a regular computer mouse (Figure 24).

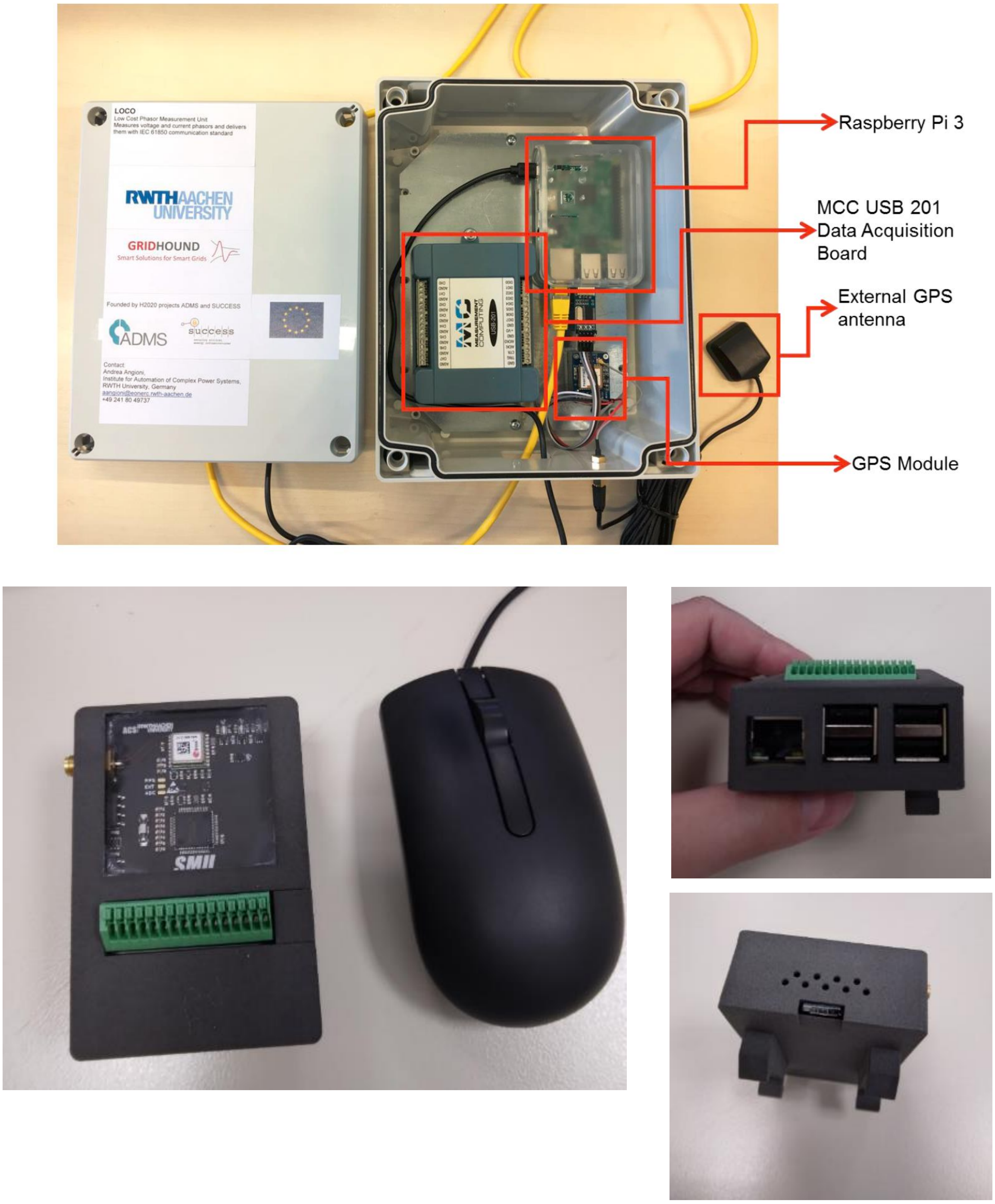


Figure 24: PMU (above) and SMU (below) for size comparison. The PMU size is roughly that of an A4 piece of paper, whereas the SMU is much smaller, comparable to a computer mouse.

The novel SMU is 3D-printed out of Nylon 12. This material is rated for operation up to 170℃ with a dielectric strength of 1-100kV/mm [29] and is therefore deemed safe to install in an MV/LV substation.

The input of the SMU is ±10V AC max. The nominal voltage on the LV side of the distribution grid in Greece is 400/230V RMS. The current rating for the components inside the pillar (LV side of the substation) is 1000A. It is therefore imperative that the appropriate sensors are selected in order to achieve accurate and reliable signal acquisition. In the process of selection and acquisition of the sensors, the following issues had to be dealt with:

1. Most commercially available voltage and current sensors have a DC output, making the equipment available very limited,
2. Due to Covid-19, there were long delays in the communication with suppliers, and
3. Due to Covid-19 and Brexit, there were very long lead times for the acquisition of the selected materials.

More specifically for the current sensors, the decision was made to utilize the existing 1000/5A current transformers that are installed in the pillars, in combination with 5A/5V AC split-core current transformers by Magnelab (SCT-0750-005 5V AC) (Figure 25). The Magnelab current transformers were custom-made with a 5V AC output, which added to the lead-time of almost 3 months in order to receive them, since they needed to be shipped from the United Kingdom.

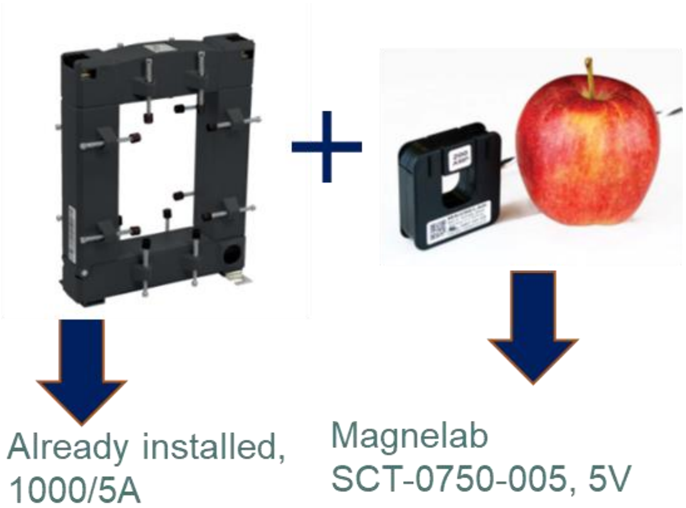


Figure 25: Combination of current transformers for SMU installation (left; existing 1000/5A, right: new current sensor connected to SMU).

Concerning the voltage sensors, the decision was made to utilize twelve commercially available voltage transformers of ABB TM 10/12 with a 230/4V AC output for intermittent service, used most commonly for buzzers. Additionally, we decided to order three Entube SE voltage dividers, rated at 250V/7V, in order to compare their performance (Figure 26) with the above-mentioned ABB voltage transformers.

The decision to use both sensors (ABB for four SMUs, Entube for one SMU) was made because of the long lead-time of the Entube voltage dividers (on order from the USA), as opposed to the ABB transformers that are available in stores in Greece. To make up for any delays, fifteen ABB transformers were bought, just in case the Entube dividers were defective or delayed much longer (fifteen transformers would cover the installation of all five SMUs). In the end, the installation went according to plan and very useful conclusions were drawn for the suitability of each sensor and presented in the following text.

As can be seen in Figure 27, the voltage divider offers a voltage signal with fewer harmonics and distortion than that of the ABB transformer. The voltage divider is more suitable for applications such as the current design of the SMU, because the quality of the input signal provided to the SMU is shown to be better than that of the ABB transformer. The optimal solution would be to have direct sensing from live line to the PMU input, in order to eliminate sensor’s fault, an option though that is not available at the current design of the PMU and would entail considerable redesign of the device.

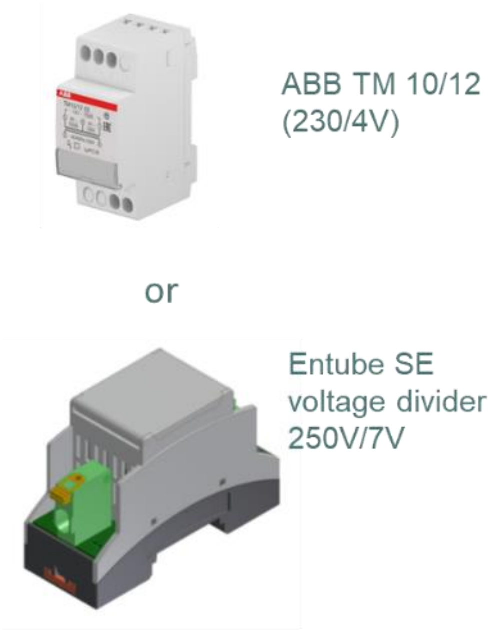


Figure 26: Voltage sensors (Above: ABB TM 10/12, below: Entube SE voltage divider).

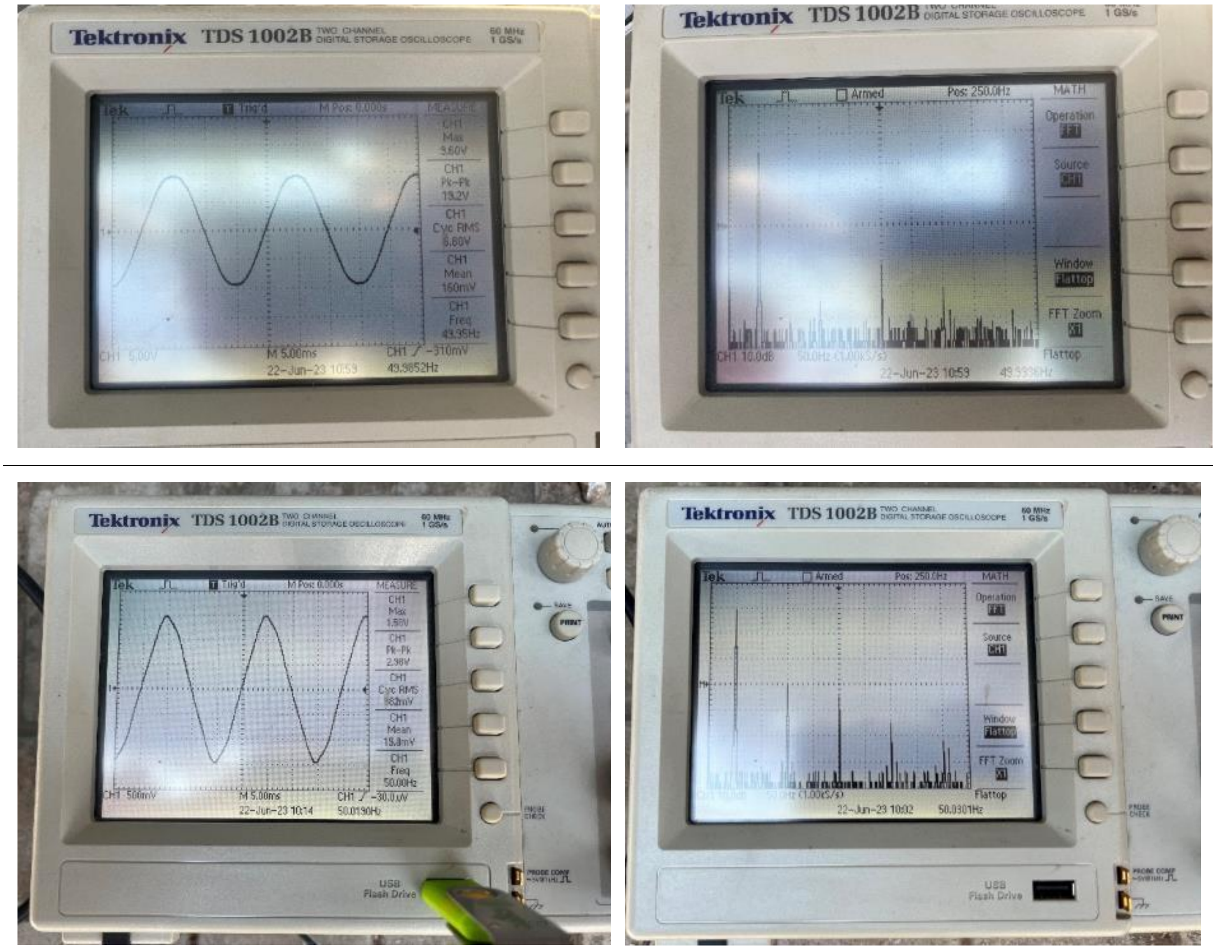


Figure 27: Voltage waveforms (left) and harmonic analysis (right) of SMUs installed with ABB transformers (below) and Entube voltage dividers (above).

The most appropriate nodes for installation of the PMUs were selected after tests based on optimization techniques of the SE tool. Out of the thirty nodes that resulted from the SE tool's optimization process, five nodes were deemed as appropriate for the PMUs installation after visual inspection of the corresponding MV/LV pillars. The criteria were:

1. A working power outlet to power the SMU inside the pillar,
2. Working current transformers to connect the Magnelab ones,
3. Available space for the SMU, and
4. One empty LV feeder (i.e., no load supplied by it) to connect the SMU without interrupting power supply to the customers.

All five substations eventually selected belong to the R210 MV feeder of the Nea Makri HV/MV substation. In order to ensure the safety of the personnel during the installation as well as the personnel that will be working in the pillars in the future, it was decided to use a 3x10A circuit breaker for every LV phase connected to a voltage sensor. Moreover, each SMU, along with the voltage sensors were placed inside a plastic 17x21 cm box, with a screw-on lid, so that the equipment is protected. The assembly of the SMUs inside the boxes happened off-site (Figure 28). Furthermore, before installation, the connectivity of the SMU was tested, by connecting the Global Positioning System (GPS) antenna and the power outlet, in order to ensure proper operation (Figure 29). All five SMUs were tested and performed as expected. Furthermore, a trial was also performed in a pillar close to the regional office of HEDNO at Mesogeia, in order to check the GPS connectivity inside the pillar (Figure 30).

Figure 28: Assembly of SMU and sensors in the box.

Figure 29: Testing of SMU (powering the SMU and GPS connectivity).

Figure 30: Trial placement inside the MV/LV pillar.

The first PMU was installed on March 7th, 2023, on node MT46. The following two on April 13th, 2023, on nodes MT02 and MT03 and the last two on nodes MT162 and MG40 on June 13th, 2023. The installation was performed by HEDNO technicians with supervision of the Platone HEDNO team. It took on average one and a half hour to complete each installation.

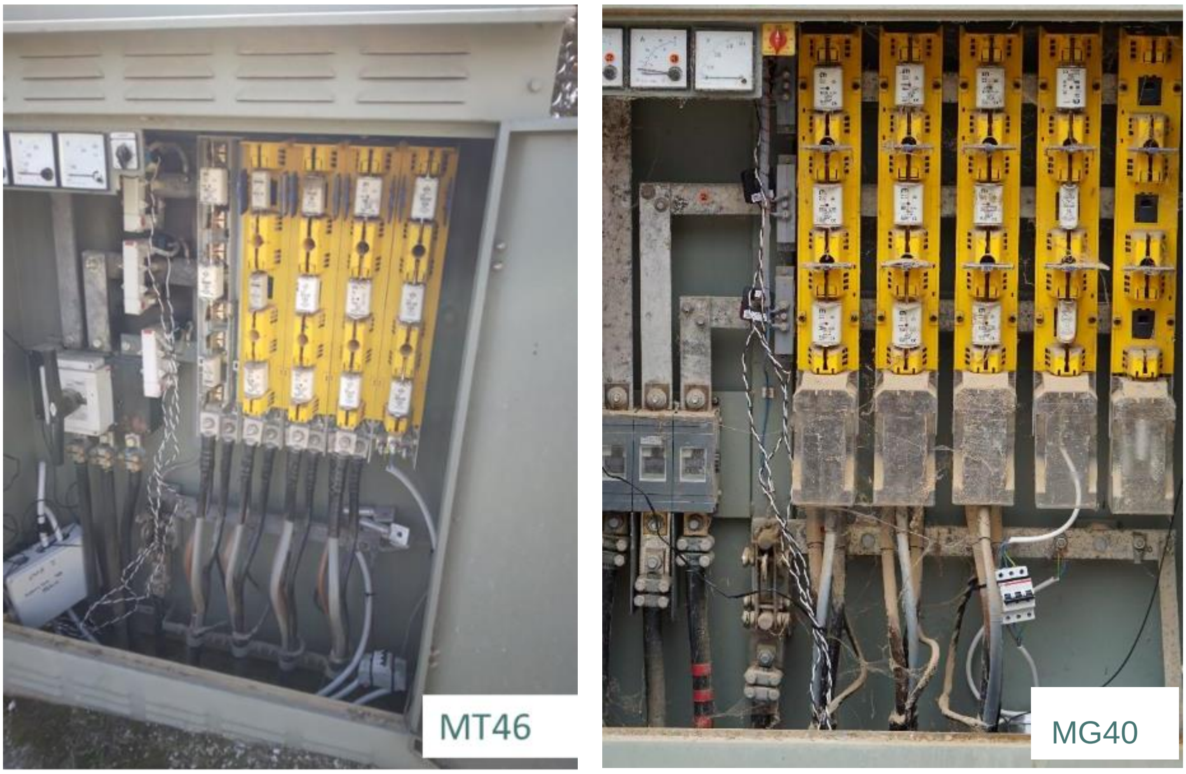
The current signals were connected to the output of the existing current transformers via the Magnelab transformers as mentioned previously. The voltage signals were connected to empty feeders in each pillar. This way, it was possible to complete each installation without disconnecting power, therefore creating minimal to no disturbance for consumers connected to these substations. Some pictures of the installation can be seen below, in Figure 31. The technicians took all necessary measures in order to work on a live substation, therefore ensuring that all HEDNO's health and safety standards were met.

Figure 31: Connection of current signals (left) and preparation for connection of voltage signals (right) in MT02 substation.

The assembled SMUs were placed in the floor of the pillars and a sticker was designed and placed on the lid of the box, to inform technicians who perform day-to-day maintenance work about the content of the box (Figure 32).

Figure 32: Sticker with Platone logo placed on the lid of the SMU boxes prior to installation.

The following pictures show the final placement of the PMUs inside the pillars (Figure 33):



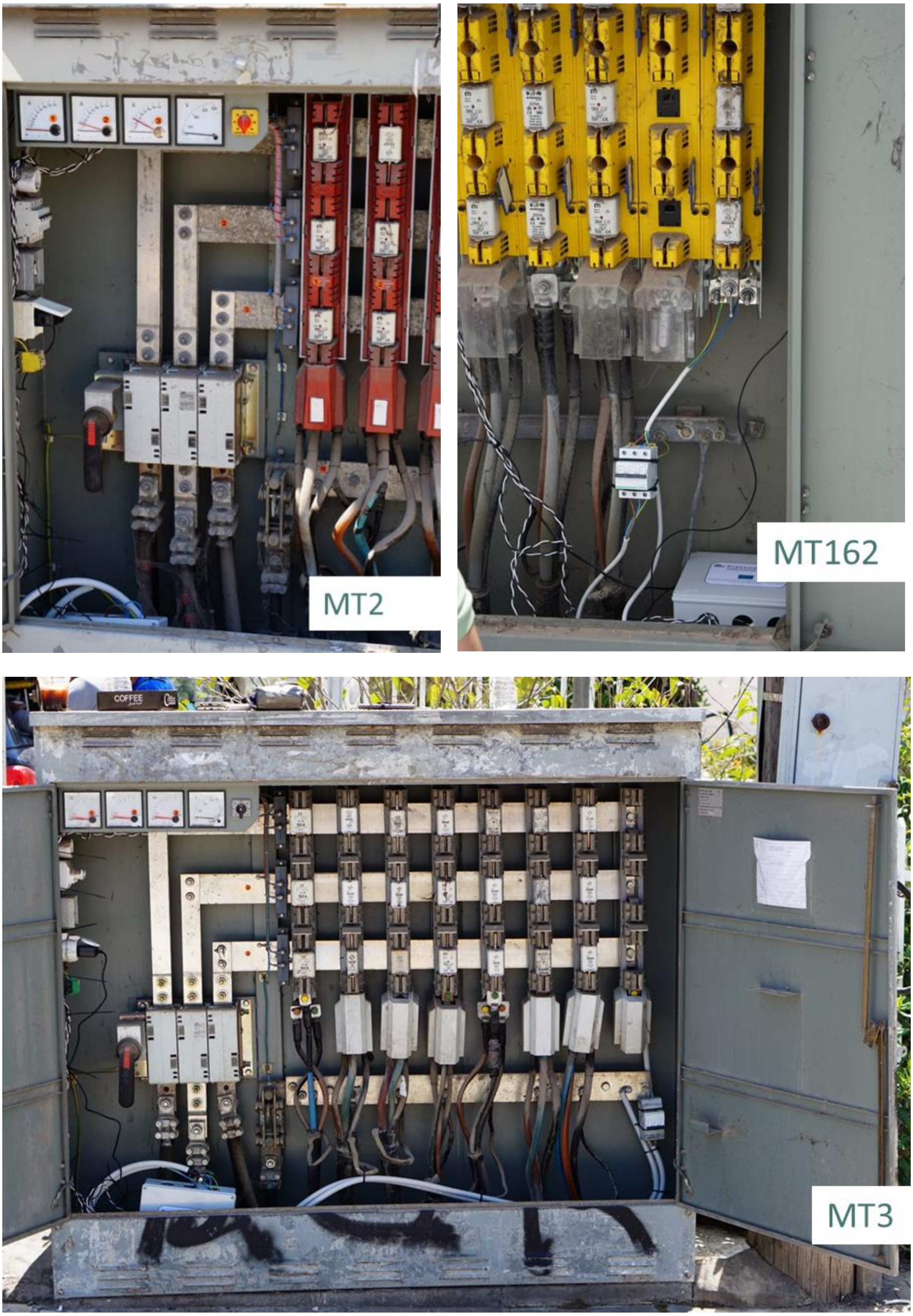


Figure 33: Pictures of the final installation of the PMUs.

3.2.6.2 Lesson learned

As already mentioned, the PMUs were designed and developed by RWTH, who provided them to HEDNO for them to realize some field installations. The PMU measurements were meant to be used as input to the SE tool for the Greek demo solutions. The commissioning of the PMUs itself as well as their operation in adverse weather conditions was intended to improve the device's TRL improvement. RWTH reported the following lessons learned based on their experience in the Greek demo application of the PMUs:

- There is very limited number of manufacturers that are able to provide equipment fitting to PMU applications. Most of the manufacturers provide secondary side signals: either DC or low-quality-measurement AC signal that cause very uncertain phase shift (such as safety transformers etc.).
- Shortages in low-level electronics components can cause significant delays for manufacturing and provision of them should be planned in advance.
- Installation on-site is a much longer process than expected.
- Flexibility of the software and its open-source nature can facilitate the integration of the SMU in other systems, and also, it can mitigate any issues arisen due to systems' incompatibility.
- Hardware components, which were used to make SMU shield electronic board, can be delivered with slightly different predefined settings, therefore the settings have to be checked carefully one by one.

Additionally, the complete process of installing the PMUs in the Greek distribution network yielded important lessons learned for HEDNO as analysed below:

- The current design of the PMUs (SMUs in their current version) requires the procurement of current and voltage sensors. One important issue faced by the Greek demo was that there is very limited number of manufacturers that are able to provide equipment (sensors) fitting to PMU applications, with most commercially available sensors having DC output, the use of which is not straightforward.
- Most of the manufacturers provides secondary side signals: either DC or low-quality-measurement AC signal that cause very uncertain phase shift (such as safety transformers etc.).
- The assembly of the final version of the SMU, with the sensors along the GPS antenna and the Global System for Mobile communication (GSM) modem requires considerable time and personnel and in case of a large-scale deployment for the DSO, it would require dedicated, appropriately trained personnel.
- The final commissioning of the PMU in the pillar requires effort and time that would make a potential future large scale deployment challenging. As mentioned above, currently the duration for a single installation is one and a half hours. In a possible subsequent redesign, it is recommended that the SMU is customizable to the needs of the DSO and comes as a plug-and-play solution.
- Apart from the aforementioned technical complexities of the SMU commissioning, the issue of procurement of equipment (sensors, cables, boxes etc.) itself adds complexity to the process and creates obstacles for a DSO the size of HEDNO.
- Since the installation of the PMUs, Greece has experienced a rather severe heat wave, with temperatures rising to 46^{o}C. It is expected that the temperature inside the pillars is much higher. Nevertheless, all PMUs seem to be working steadily.
- During data acquisition there were also some issues encountered, related to software settings in the hardware components of the SMU electronic board, making it imperative to check each SMU separately. This issue could be problematic in a large-scale deployment case and should be dealt with in the first stages of the assembly of the SMU.
- In the current implementation, the antenna of the GPS is placed inside the pillar. In tests that were performed (Figure 30) the led indicator shows that the PMU is receiving a GPS signal. However, assessing the data received after the PMUs installation as well as the RWTH partner's recommendations, it became evident that both the GPS signal availability and the measurements' accuracy is impacted significantly by the antenna being in an enclosed space. GPS signal is crucial as it ensures measurements' synchronization and keeps the

measurements' error within the necessary limit margin. In the current form of the pillars, it is problematic to mount the antenna outside the pillar and guarantee that it will not be destroyed or stolen. So, it is suggested that a future design of this PMU comes as a compact solution, such that it can be mounted on the pylons that support the transformer of the substation at a non-reachable height ensuring the antenna remains outdoors, and hence, the GPS signal availability.

Overall, in its current form, the SMU presents an important test case for Platone in general and for HEDNO in specific, but for a DSO with this size, the possibility to scale up the deployment of these devices depends on potential future upgrades of the prototype based on the aforementioned points.

4 Implementation of Use Cases

The Platone UCs for the Greek Demo are extensively described in D4.1. A template, based on the UC Methodology outlined in IEC 62559 [30], was used for the definition of the UCs. In this section, a brief description of each UC is provided, along with their scope, objectives, and how they were ultimately fulfilled. The primary focus is to highlight any modifications that were made throughout the duration of the demo and the rationale behind such modifications. Regarding the results of the UCs, Chapter 5 provides updates on the KPIs that evaluate the performance of the UCs and the Greek demo as a whole.

The primary objective of the Greek demo is to assess the effectiveness of the Platone architecture and investigate whether the innovative approach of implementing variable, instead of a flat, network tariffs, incentivizes prosumers to provide their flexibility leading to the optimal DERs' dispatch for the distribution network. Additionally, the Greek demo incorporates a SE tool developed by NTUA, grid forecasting techniques, and real-time grid monitoring, with the aim of enhancing distribution network operation and allowing for further exploration of diverse dispatch scenarios. Furthermore, novel low-cost PMUs developed by RWTH are installed and tested in the field, by commissioning them at selected nodes, contributing to the network observability and providing more accurate results for the demo's algorithms.

The realization of the Greek demo was achieved through the definition and execution of five different UCs. Four of these (UC1-UC4) primarily focus on evaluating the tools and services described in section 3.2. UC-5, on the other hand, is an IT-oriented UC associated with the actual implementation of the Platone platforms (DSOTP and BAP) and the deployment of PMUs within the Greek demo.

4.1 UC-GR-1 - Functions of the State Estimation tool given conventional measurements

4.1.1 Objective - Scope

The primary goals of the UC were to improve confidence in actual measurement data collected from the network and the accuracy of load forecasts, as well as to capture the current operational state of the network in real-time. UC-GR-1 was dedicated to the examination of the capability of the SE tool to achieve observability for the Mesogeia pilot site, based on the pre-existing metering infrastructure. The network state estimate in general serves as an input for the applications used in distribution network management and thus, is the first and most important step that enables the modernization and evolution of the DSO.

4.1.2 Description - Implementation

The UC aims to evaluate the ability of the SE tool to determine the real-time state of the distribution network. The network model (topology) is known a-priori with a good degree of certainty. Also, a measurement set, which comprises actual and historical measurement data is obtained from the pre-existing dispersed metering devices (SCADA, AMR, GIS) installed throughout the network and is available for real-time operation purposes. These measurements include power flows and voltage magnitudes at the top of the distribution feeders, power injections from distributed generation units, loads records from MV customers, and load pseudo-measurements for aggregated consumer demand at MV/LV transformer level.

All the measurement data are certified through the BAP and are transmitted via an MQTT broker to the SE tool deployed in the DSOTP at HEDNO premises. Once the SE tool receives all the necessary input data (topology and measurements), it ensures that the network is observable based on the available measurements. Subsequently, it calculates the estimated state vector, which includes voltage magnitudes and angles, as well as active/reactive power values for all load buses in the network. The UC sequence diagram depicted in Figure 34 provides a visual representation of the implemented procedures and processes of the UC-GR-1.

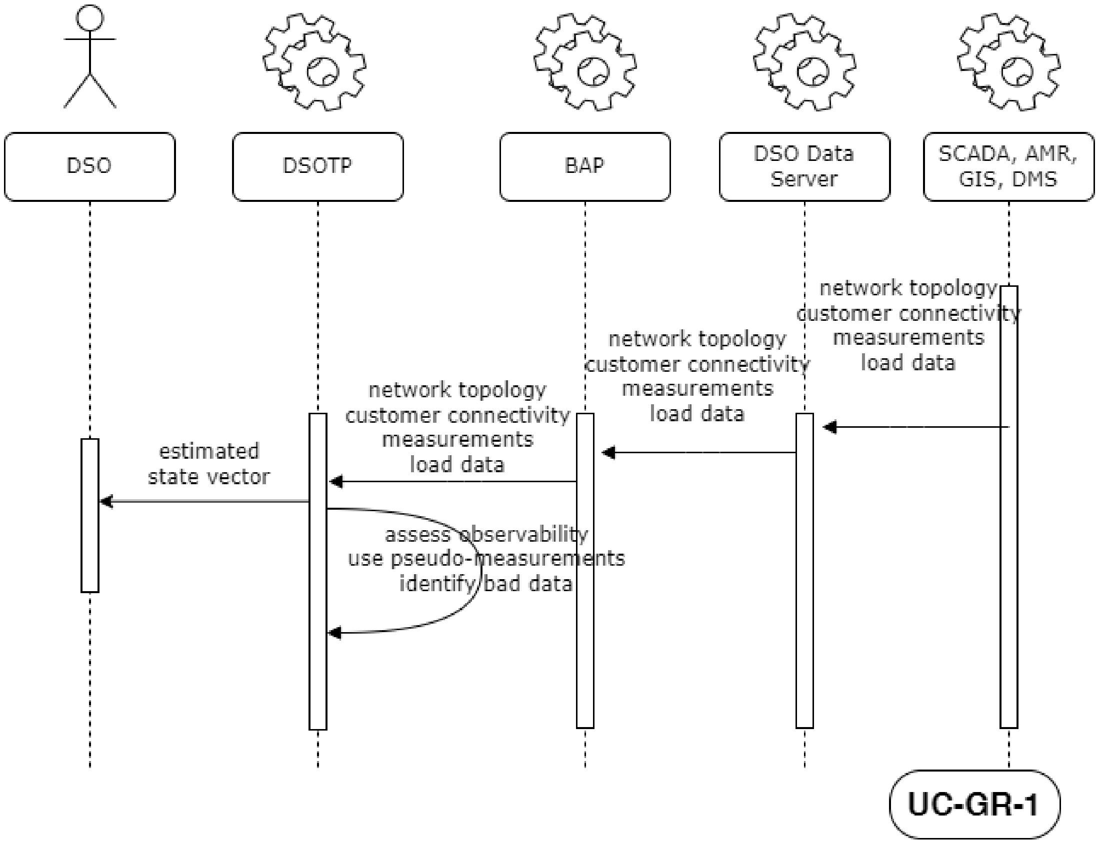


Figure 34: Sequence diagram UC-GR-1.

The implementation of UC-GR-1 considers two different scenarios taking into account the pre-existing metering infrastructure. In Scenario 1, the study aims at the achievement of quality SE using pseudo-measurements. In Scenario 2, the objective is to investigate the risk of loss of observability and to examine solutions to reinforce the observability of the Mesogeia pilot site by incorporating additional measurements to compensate for any missing ones.

In the baseline scenario, a typical operational framework is considered in which HEDNO operates the network of the Mesogeia site with all switching devices being at their normal condition. The SE tool is required to render the grid observable using pseudo-measurement to supplement the limited set of actual measurements and, thus, to compute the maximum likelihood estimate of the grid state.

As regards the Scenario 2, the occurrence of missing or inconsistent measurement data is considered which might render the test network unobservable. With the objective of achieving observability, realistic options for additional or alternative data which can substitute the missing ones as well as their impact on the performance of the SE tool are studied.

4.1.3 Main findings

Offline simulations in MATLAB software based on actual measurement data from the Mesogeia pilot site (15-min time resolution) are carried out to test the SE tool. Features from the (MATLAB based) open-source toolbox for electric power system simulation and optimization, MATPOWER [31] have been deployed to set up the simulation framework. The PTI PSS/E "raw" format [32], was used to store and exchange the data (network topology, measurements, and SE results) between the components of the SE tool.

It needs to be noted that for the calculation of the KPIs GR 01 – 03, a reference, "true" state should be set. Since the actual grid state cannot be acquired, a power flow solution based on the available SCADA and AMR measurements, with the latter being processed as real-time data (and not delayed as they actually are) is used to derive the best feasible approximation of the actual state which is assumed to be the reference. Obviously, the forenamed 3 KPIs can only be used inside a controlled test environment, thus, not during the demonstration of the SE tool in real-world conditions. The KPI levels achieved by the SE tool in the simulations of the UC are discussed in section 5.2.

The main finding from the study conducted in Scenario 1 is the negative effect of the low measurement redundancy on the error filtering capacity of the SE tool. The limited amount of pre-existing data (actual and pseudo-measurements) provides marginal measurement redundancy. Besides, although they can provide several benefits to SE in distribution grids, pseudo-measurements cannot compete with actual data in terms of measurement redundancy. As a result, the SE tool can achieve good accuracy in state estimates only for specific areas of the Mesogeia pilot site. With regard to convergence properties, the most important finding is the accomplishment of consistent algorithmic convergence for all SE executions; a fact which indicates that the tuning measurement weights is effective, i.e., the relative levels of measurement weights are adjusted properly.

Concerning Scenario 2, the criticality of the single available measurement of voltage magnitude from the slack bus (HV/MV substation of Nea Makri), whose loss leads to lack of grid observability, is a major issue. The related analysis led to the conclusion that the addition of new measurement of voltage magnitudes to the pre-existing dataset is a prerequisite for the reinforcement of grid observability and reliable operation of the SE tool.

Overall, the performance of the SE tool given the pre-existing metering infrastructure is low as regards accuracy and clearly acceptable as regards convergence rate. Therefore, the reinforcement of the metering infrastructure is essential for the support of the SE tool.

4.2 UC-GR-2 – PMU data integration into the State Estimation tool

4.2.1 Objective - Scope

The purpose of the UC-GR-2 was to integrate synchrophasor data into the SE tool in order to reinforce the network observability and the measurement redundancy. Hence, the UC-GR-2 aims to test the smooth integration of the data derived from SMUs into the set of conventional measurements already in place (SCADA, AMR).

4.2.2 Description - Implementation

The first step for the implementation of the UC is the determination of the nodes assumed to host SMUs, which record the nodal complex voltage and the current phasor at an adjacent line (overall, 2 phasors are measured per SMU). The metering units to be installed can be placed in an empirical manner (transformer with high capacity, upper part of feeders) or via a sophisticated algorithm which optimally allocates them according to a specific criterion (SE accuracy, observability etc.). Both approaches are used; the first one, for reasons of conducting extensive offline simulations, while the second one for the testing of a method for optimal meter placement which was applied to a portion of the Mesogeia pilot site [33].

After the allocation, the main goal of ensuring the smooth integration of synchrophasor data relies on the determination of a time window within which all available measurements (conventional and synchronized) have been recorded so that they can be introduced as snapshot into the SE tool and, importantly, the proper weighting of them. What needs to be examined is the overall impact on the performance of the SE tool and if the expected improvements can enable the SE tool to meet the high-quality real-time operational standards for distribution management applications. The UC sequence diagram, depicted below (Figure 35), provides a visual representation of the implemented procedures and processes of the UC-GR-2.

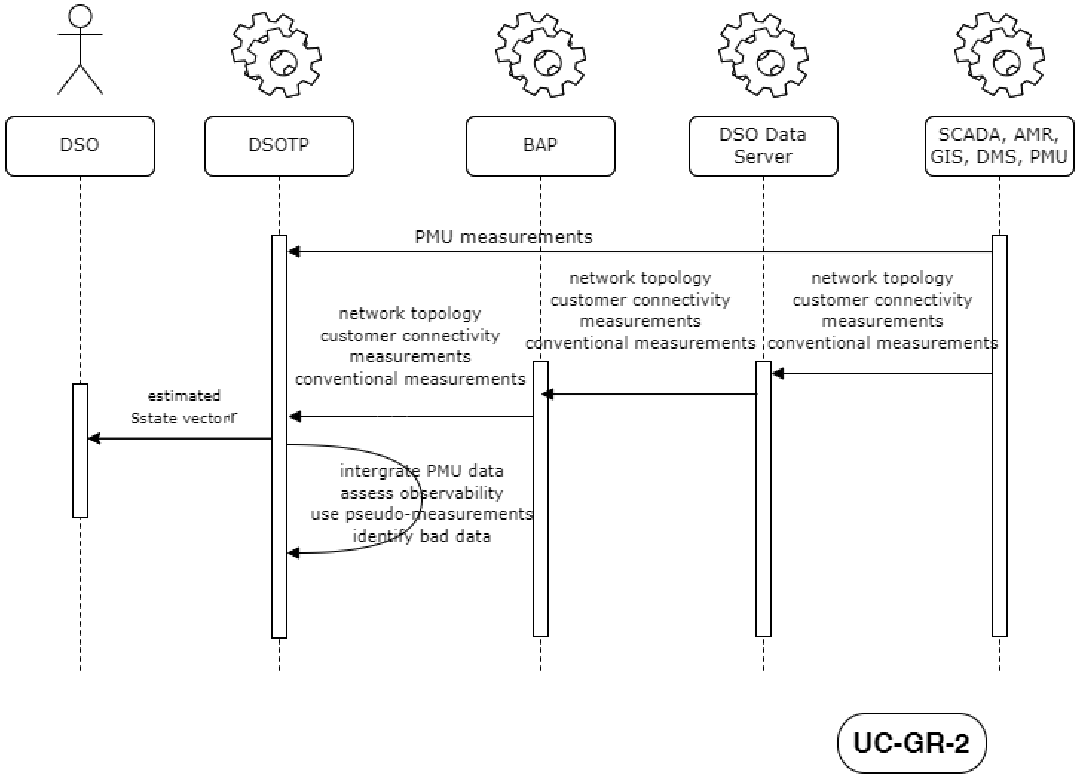


Figure 35: Sequence diagram UC-GR-2.

The related scenario for UC-GR-2 assumes the installation of 20 SMUs at strategical locations within the Mesogeia pilot site (selected empirically). As a result, synchronized phasor data becomes available and is fused with the pre-existing conventional measurements, in a unified dataset. The SE tool processes the measurements in order to deliver the maximum likelihood estimate of the grid state. The performance of the SE tool in terms of accuracy and convergence speed is investigated.

4.2.3 Main findings

Similar to UC-GR-1, offline simulations were carried out to test the SE tool. Given that the real-life installations of SMUs took place during the last months of the Platone project, due to the delayed procurement of sensors required for their operation, the simulations of UC-GR-2 in D4.2, were exclusively based on manufactured data based on the nominal characteristics of the grid (rated transformer capacity, power factors etc.). To generate realistic measurement sets, a power flow algorithm was deployed. The performance of the SE tool is evaluated to quantify the improvements gained from utilizing high quality information provided by SMUs, compared to the pre-existing metering infrastructure. Therefore, the same KPIs as the ones presented in section 4.1 and UC-GR-1, are computed to assess the SE tool. Further information regarding the simulation framework and the configuration of the assumed 20 SMUs placed in the test network can be found in D4.2.

The KPI values attained by the SE tool in the UC, are elaborated in section 5.2. As already mentioned, the KPIs GR 01 – 03 cannot be calculated in actual operation of the SE tool, thus, they are not studied during the demonstration phase.

The major finding of the UC refers to the confirmation of the positive impact of the addition of synchrophasor data on the SE tool. The algorithm achieves excellent performance with increased convergence speed and yields precise state estimates for the Mesogeia pilot site. This outcome is due to the increased measurement redundancy which reinforces the error filtering capacity of the SE tool, and to the expedient tuning of the measurement weights. It is noteworthy that the assumed number of installed SMUs for offline simulations is larger than the units actually installed in-field. Yet, the obtained results assuming 20 SMUs for the UC indicate such a drastic improvement in the performance of the SE tool that the deployment of SMUs even in small numbers is expected to vitally contribute to the development of quality SE.

An additional finding pertains to the crucial aspect of the synchronization between the conventional and SMU data. A simple, yet effective scheme is used for the construction of measurement snapshots which are processed by the SE tool in real-world operation. However, a more sophisticated solution based on the existing literature can be devised for further improvement. Finally, as regards the locations of installed SMUs and the phasors to be measured per individual unit, the experience from their deployment in the Mesogeia pilot site shows that technical constraints regarding specific installation spots (MV/LV transformers) prevent the real-world application of the proposed optimal placement scheme (i.e. the placement of all SMUs initially planned for, at the optimum for SE purposes locations). In other words, the SMUs are placed at non-optimal locations, a fact which certainly affects the expected outcomes and complicates the implementation of the designed SE methodology.

4.3 UC-GR-3 – Distribution Network limit violation mitigation

4.3.1 Objective - Scope

The aim of UC-GR-3 was to improve the efficiency of the network operation while respecting operational limits (voltages, lines overload). This was meant to be achieved through the utilization of flexibility tools, such as variable network tariffs. Additionally, the UC aimed to test the combined implementation of the two separate tools developed by NTUA, namely the SE tool which was presented in subsection 3.2.3 and provides real-time estimation of the network's state and the algorithm for optimal DER control which was described in subsection 3.2.4 and sets the value for the variable network tariffs.

4.3.2 Description - Implementation

RES, including PVs and customers with flexible loads, are connected to the distribution network at the MV level. Their flexibility can be enabled through appropriate incentives provided by the DSO's tools and services. The SE tool utilizes a set of inputs including the measurements from various sources such as AMR, GIS, SCADA, and PMUs along with the network topology to accurately determine the state of the network. This knowledge combined with historical consumption data and weather forecasts allows the optimal DER control algorithm to be employed which provides a variable network tariff scheme as described in subsection 3.2.4.

The variable network tariffs are then communicated to the prosumers to incentivize them to utilize their flexibility and align their operations with the network's needs. Thus, the potential for the network to exceed its physical limits such as voltage and thermal line constraints is appropriately managed, thereby avoiding violations and the need for demand and/or generation curtailment. The UC sequence diagram depicted in Figure 36 provides a visual representation of the implemented procedures and processes of the UC-GR-3.

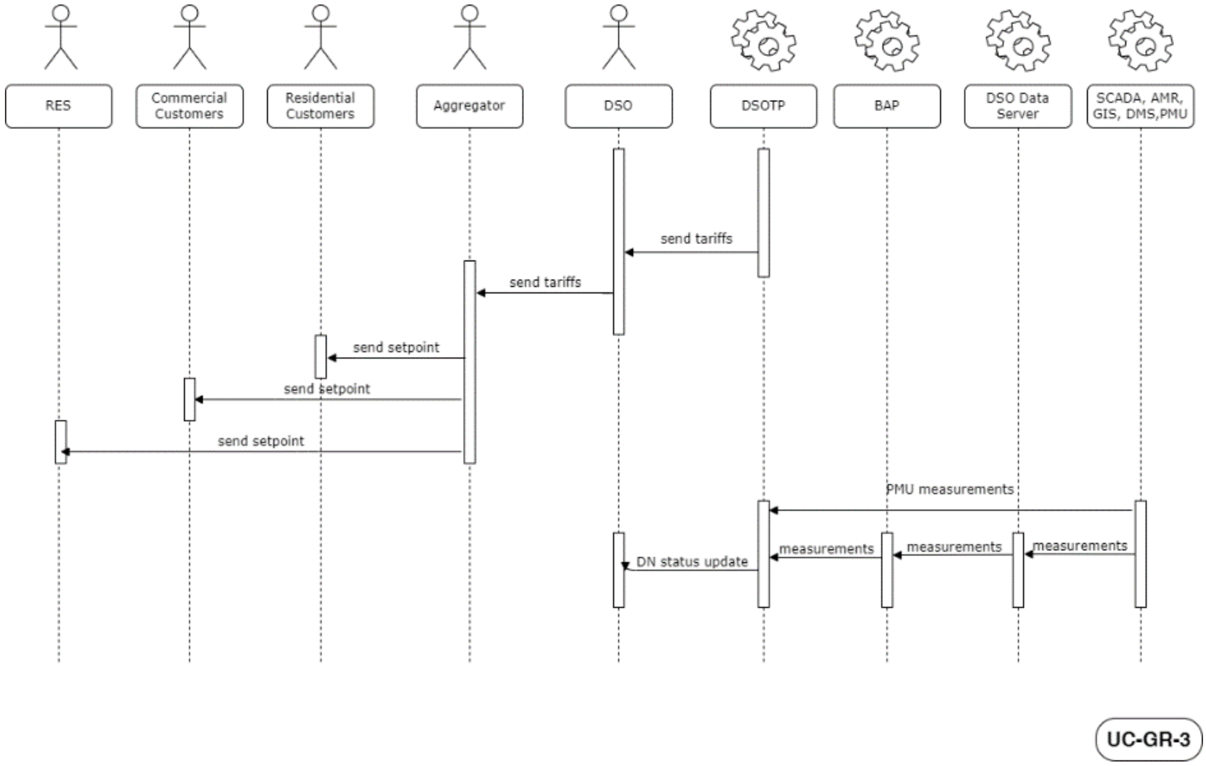


Figure 36: Sequence diagram UC-GR-3.

4.3.3 Main findings

The UC-GR-3 scenario assumed that the DSO communicates the network tariffs to the prosumers in a day-ahead context. The results of this approach were evaluated by comparing it with two other scenarios: the BaU scenario of flat network tariffs on the one hand and the theoretical optimal scenario where the DSO directly controls all available flexibility and has perfect knowledge of the network state on the other hand. This comparison allows for a comprehensive assessment of the effectiveness of the variable network tariff scheme in improving network operation and maximizing the utilization of flexibility resources. A key finding of the UC-GR-3 implementation was that the methodology developed incentivises significant flexibility provision compared to the baseline (BaU) scenario and manages to achieve considerable effectiveness in terms of reducing network operational costs -specifically curtailment costs- when compared to the theoretical optimal scenario. The KPI values related to the algorithm for optimal DER control in the UC as well as further insights into the main findings are elaborated in sections 5.1 and 5.2.

4.4 UC-GR-4 – Frequency support by the distribution network

4.4.1 Objective - Scope

UC-GR-4 aimed to enhance the operational state of the distribution network in response to a frequency restoration reserve activation request from the TSO. This is accomplished by leveraging flexibility tools that maintain compliance with line and voltage limits of the distribution network while satisfying the TSO request. By utilizing these flexibility tools, the distribution network can effectively contribute to the overall stability and reliability of the power system.

4.4.2 Description - Implementation

In UC-GR-4 the set of measurements provided as input for the SE tool which in turn enables the use of variable DUoS tariffs, is the same as the ones previously described in subsection 4.3.2. However, the difference lies in the Aggregator, representing the customers with flexible loads, who receives a frequency support activation request from the TSO, also communicated to the DSO. Then, the DSO calculates a new set of network tariffs that reflect the network's situation and communicates them to the

Aggregator. The algorithm implemented for the calculation of these tariffs is described in subsection 3.2.5. Flexible loads respond to these tariffs, effectively addressing the frequency support request, while ensuring the operational safety of the distribution network. The UC sequence diagram depicted in Figure 37 provides a visual representation of the implemented procedures and processes of the UC-GR-4.

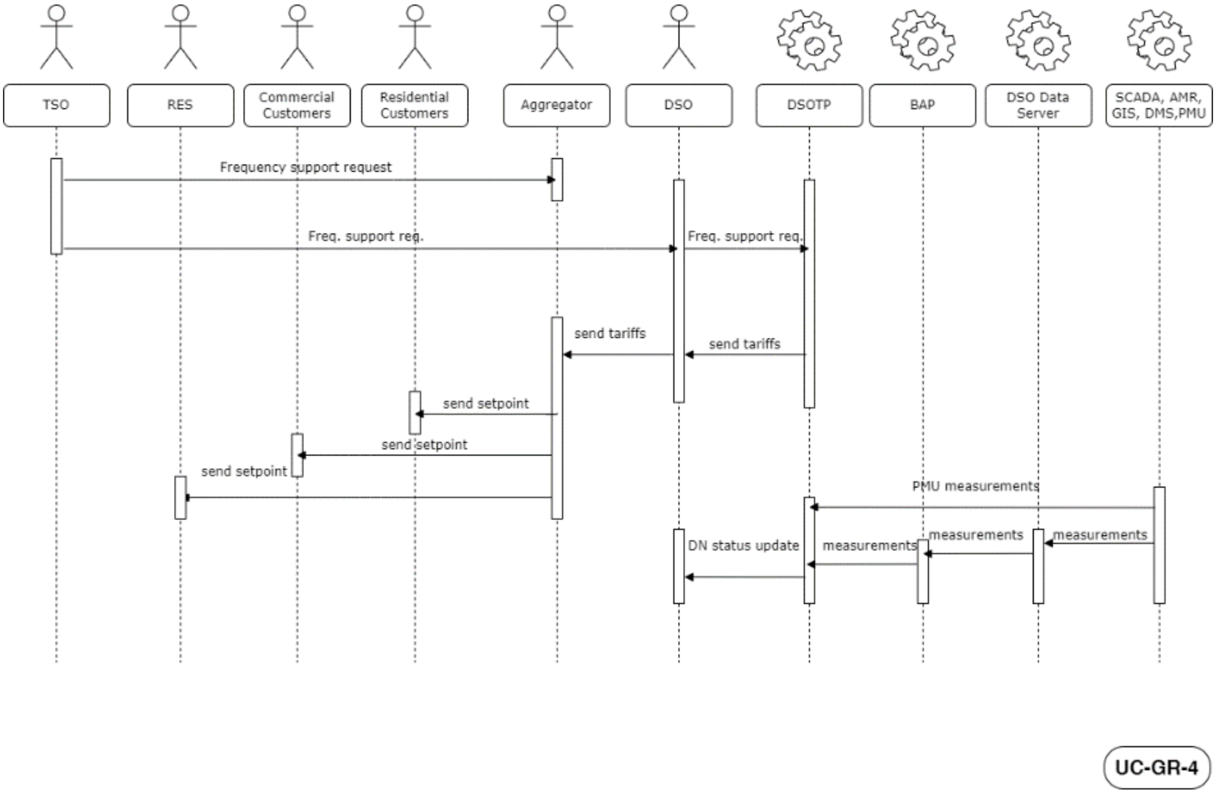


Figure 37: Sequence diagram UC-GR-4.

In the scenario implemented within UC-GR-4, a frequency support request from the TSO needs to be resolved while the DSO ensures the network stability using variable network tariffs. It is important to note that similar to UC-GR-3, since the regulatory framework regarding flexibility provision is at its early stages in Greece with the details of it not yet finalised, UC-GR-4 could not be tested in a real-life environment. Hence, it was decided that the entities involved would be simulated. As a result, an actual frequency support request from the TSO was not feasible and instead, it was simulated. Additionally, before receiving the TSO's request, the day-ahead scenario from UC-GR-3 is in effect. After receiving the TSO's request, a real-time scenario is implemented and new network tariffs are calculated and communicated to the relevant stakeholders for the remainder of the day.

4.4.3 Main findings

The problem formulation in UC-GR-4 is non-linear due to the various types of violations observed in the network. However, the developed solution achieves optimal DER control by taking into account this complexity with the algorithm’s curtailment actions resulting either from a voltage violation or a line congestion or both. Even if the potential network violation events get resolved, they are inherently interconnected, making it unfeasible to distinguish between them and identify the specific cause of the curtailment. Consequently, it became evident that the KPIs originally linked with UC-GR-4, as mentioned in D1.4, would not reflect meaningfully the results of the solution proposed through the use of RT DUoS tariffs. Instead, the effectiveness of the methodology tested in UC-GR-4 could be easily assessed by calculating the costs incurred by the DSO with and without the proposed framework of the RT DUoS tariffs. The main conclusion drawn from the year-long analysis performed in D4.3 as analysed in chapter 3.2.5 of the current document, is that a RT tariff scheme, complementary to the DA DUoS tariffs, can significantly reduce operational costs through the utilization of DER flexibility for balancing or reserve services to the TSO (Table 4) in cases where distribution network congestion problems occur.

4.5 UC-GR-5 – PMU integration and Data Visualization for Flexibility Services Management

4.5.1 Objective - Scope

The two main objectives of UC-GR-5 were to increase network observability by the installation of advanced metering systems (PMUs) and to integrate data coming from various sources within the DSOTP. To ensure data security and anonymity, all data were intended to undergo processing through the BAL. The integration of Platone platforms and the testing of appropriate communication protocols were necessary, so that eventually a single point of data delivery for all relevant stakeholders was established. Additionally, a User Interface (UI) needed to be developed to facilitate the use of available tools and services by the DSO personnel and any future stakeholders related to the pilot project. UC-GR-5 in essence aimed to verify and measure tangible outcomes of the Platone architecture in the case of the Greek demo.

4.5.2 Description - Implementation

UC-GR-5 is an overarching UC in the sense that it does not investigate a specific method or scenario, but it is a study applicable to all previous UCs. It explores the actual PMUs' installation, and how Platone platforms empower the Greek demo in terms of data integration, data security, and data visualisation. Data that become available after the completion of the UC-GR-5 are not only raw network data, but also data resulting from the implementation of the previous UCs, i.e., applications of the SE tool as well as the algorithm for optimal DER control via variable DUoS tariffs.

PMUs are installed in critical network nodes to increase network observability. PMU measurements along with other DSO data (network topology, customer loads, PV production, etc.) are integrated in the DSO Technical Platform to be visualised in a UI, so that DSO can make use of tools and services developed in the project. The aforementioned data is going through the BAP developed in the project to ensure data access security and data integrity. The UC sequence diagram depicted in Figure 38 provides a visual representation of the implemented procedures and processes of the UC-GR-5.

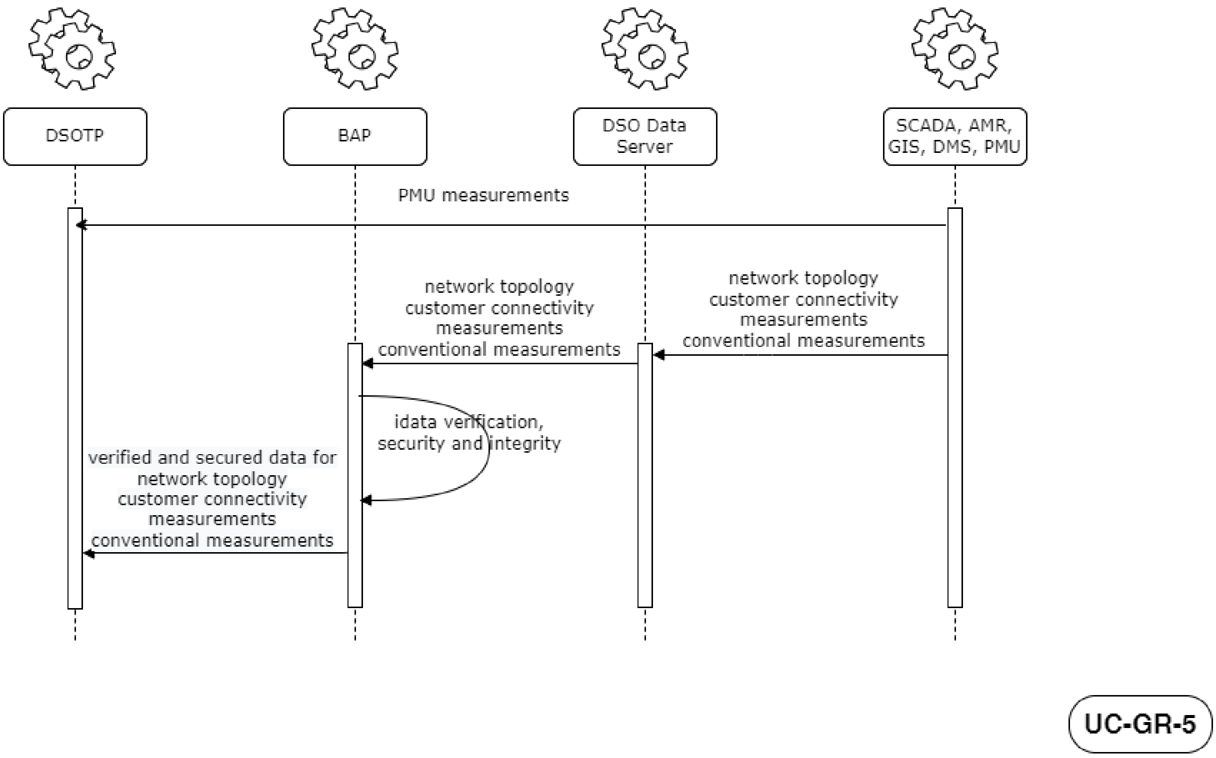


Figure 38: Sequence diagram UC-GR-5.

4.5.3 Main findings

The DSO operates the distribution network and needs to handle the data coming from various systems such as SCADA/DMS, AMR, and GIS. The DSOTP performs successfully the synchronisation of the data coming from these different sources and systems in real time, providing the DSO with the raw network data, as well as the technical capacity (i.e. a unified network measurement dataset) for using services such as the SE or the variable DUoS tariffs. Also, a Greek-demo specific UI was developed within the DSOTP so that the aforementioned data are visualised. During the design phase of the Greek demo, it was agreed that there would not be any real benefit of anonymising and/or securing the PMU measurements using the blockchain technology. Hence, all other data except for PMUs' data are verified and secured via the BAP that was developed within Platone.

As already mentioned, data coming from various conventional sources get integrated into the DSOTP providing the DSO with an adequate level of network observability. With the view of adding advanced metering systems in the network, low Cost PMUs were installed at the Mesogeia area in critical network points and nodes, where there was either limited observability or it was required to increase awareness due to the DER and prosumers bidirectional power flows. In addition, PMU data were integrated in the DSOTP following a data collection plan that serves the functionalities of the SE tool developed for the Greek demo. Measurements from PMUs enhance network awareness providing GPS-synchronised data of high granularity (every 15 minutes within the Greek demo context, although a higher level of granularity – up to 0.1 seconds – can be supported by the PMUs provided). Additionally, the commissioning of the PMUs increases the number of nodes observed in a cost-effective manner.

5 Assessment of KPIs

The KPIs for evaluating the Greek demo were initially defined in conjunction with the UCs in the first year of the project in D4.1. As the project progressed over the next two years, adjustments were made to the selection and formulation of the KPIs for the Greek demo. So, the final list of the project KPI, along with the demo-specific KPIs can be found in D1.4. Reaching the end of the Platone project, the final results of all the KPIs are extensively presented in D1.7. In this document, the calculation methodology and target values of the KPIs relevant for the Greek demo are also described.

This chapter elaborates on the main findings mentioned in the previous chapter, organized and presented per UC. It also provides an overview of the outcomes of each KPI as well as the insights that emerged from these results. The comments on the results along with the overall experience of the Greek demo contribute to the conclusions presented in Chapter 7 of the current report.

5.1 Project KPI

A project KPI refers to a KPI that is common across at least two different Platone demonstration sites. The calculation methodology and target values for all project KPIs are described in D1.2. It is important to note that in D1.4 [5], KPI_PR_05 “Distribution Network Hosting Capacity” was removed from the Greek demo’s list. This decision was based on the findings presented in D4.3 and D4.4. The same results also highlighted the relevance of another project KPI, namely KPI_PR_04 "Flexibility Effectiveness", which was subsequently added to the KPIs for the Greek demo.

In this subchapter, KPI_PR_04 is briefly presented along with its results and accompanying comments. The calculation of this KPI is carried out during UC-GR-3, as indicated in Table 5. Detailed information on the methodology used to calculate this KPI and its specific target values can be found in the relevant documentation already mentioned.

Table 5: Overview of the Greek Demo Project KPI relation to the UCs of Platone.

KPI ID	KPI name	UCs
KPI PR 04	Flexibility Effectiveness	UC-GR-3

5.1.1 KPI_PR_04 Flexibility Effectiveness

KPI_PR_04 evaluates the effectiveness of the methodology tested in the Greek demo in motivating DER flexibility. As mentioned in subchapter 4.3, the results of UC-GR-3 are compared to two reference scenarios: the BaU scenario of flat network tariffs and the theoretical optimal scenario of perfect coordination by the DSO to harness all available flexibility (centralized OPF). The flat tariff scenario represents 0% effectiveness as it is inherently unable to motivate any flexibility, while the theoretical optimal scenario represents 100% effectiveness. The proposed method stands in between the two.

This KPI measures the percentage that the method of variable DUoS tariffs achieves in terms of reducing network operational costs, specifically curtailment costs, on a DA scheme (hourly and hourly-locational) as presented in subchapter 3.2.4. Curtailment costs, C, include emergency load and generation shedding caused by network congestions. The formula used to calculate the KPI is as follows:

$$KPI_{PR_{04}} = \frac{C^{prop} - C^{BaU}}{C^{OPF} - C^{BaU}}$$

where C^{prop} is the curtailment cost of the proposed method, C^{BaU} is the curtailment cost of the BaU case and C^{OPF} is the curtailment cost of the theoretical optimal case.

Extensive simulations were conducted under realistic conditions over a one-year span, resulting in the total curtailment costs (€) and efficiency (%) for four clusters ($k = 4$) of day-types during the design-phase of the variable DUoS tariffs Table 6 presents the results of the algorithm for optimal DER control when the true state and when the estimated state of the network are known to the DSO (Figure 3) [21]. The estimated state corresponds to the network state after the deployment of the SE tool while the true state represents perfect knowledge of the network state.

Table 6: Out-of-sample total curtailment costs (€) and efficiency (%) for k=4 using the true and estimated state [21].

	Estimated state		**True state**	
Scheme	Curtailment costs	Efficiency	Curtailment costs	Efficiency
Flat	5,402.8	0%	-	
Hourly	3,415.6	55.9%	3,415.6	68.4%
Hourly-loc	3,124.5	78.5%	3,124.5	78.5%
Optimal	-		2.499,3	100%

The results of the method and the KPI values are presented in the left half of the table, where the estimated state is used in all steps. The right half of the table shows the same results for the case where the true state of the network was known in all steps. This comparison allows for quantifying the efficiency lost due to the deployment of the SE tool and the lack of knowledge of the true state. The decrease in the efficiency values for the Hourly and the Hourly-loc schemes are 12.5% and 12.7%, respectively. These differences cannot be attributed to the design phase of the tariffs as it is almost entirely due to imprecise curtailment actions during the daily operation.

As shown in Table 6, in an Hourly DUoS tariffs scenario, the method proposed motivates effectively DER flexibility and 55.9% of the theoretical optimal is achieved. This percentage increases to reach 65.8% of the theoretical optimal when DUoS tariffs that vary both hourly and locally are employed (i.e., in the Hourly-Loc DUoS tariffs scenario). It becomes evident that the DUoS tariffs' design tool that was developed for the Greek Demo within Platone incentivises significant flexibility provision compared to the baseline (BaU scenario).

Table 6 cannot tell us how much efficiency from using the estimated state is lost during the design and how much during the validation phase. In other words, it cannot be concluded whether the loss of accuracy due to the use of the estimated state affects more the clustering, and consequently the day-types or the curtailment decisions of the DSO during the daily operation. If we assume the DSO has magically knowledge of the true state solely during daily operation, then the efficiency of the two granular schemes deviates only by few decimal percentage points, e.g., < 0.1% for the Hourly-loc scheme. This tells us that most of the efficiency is lost during the daily operation. This result is expected because the tariff design employs clustering and day-types which are an average of many samples, hence, the randomness of the SE error is eliminated.

5.2 Demo KPIs

This section provides an overview of the demo-specific KPIs and evaluates their results. There is a total of fifteen demo KPIs, which were presented in D1.4 and their relation to the UCs of the Greek demo is also presented in Table 7. The first seven KPIs are associated with the evaluation of the SE tool and are calculated based on the results of UCs 1 and 2. These UCs assess the SE tool's performance while utilizing data coming from pre-existing metering infrastructure and data incorporating PMU measurements. It should be noted that KPI GR 01 to KPI GR 06 were calculated upon completion of task 4.2 in M15 (November 2020) for the purposes of D4.2. The results obtained were used for further improvements on the remaining activities of the Greek demo.

The next five KPIs correspond to the assessment of the algorithm for optimal DER control and the design of variable DUoS tariffs. The results for these KPIs were obtained from the completion of the UCs 3 and 4. In these UCs, tariffs are initially designed in a DA context and then adjusted in RT based on a flexibility request from the TSO to the DSO.

Lastly, the final three KPIs quantify the results of the UC-GR-5 which focuses on the installation and integration of PMUs as well as the visualization of data, tools, and services in the DSOTP. Overall, this section highlights the KPIs related only to the Greek demo, the corresponding UCs, and the calculated results for each KPI providing a comprehensive evaluation of the proposed solution of the Platone Open Framework's as tested in the Greek pilot.

Table 7: Overview of the fifteen Greek Demo KPIs relations to the UCs of Platone.

KPI ID	KPI name	UCs
KPI GR 01	Root mean square error (RMSE)	UC-GR-1; UC-GR-2
KPI GR 02	Relative percentage error (RPE)	UC-GR-1; UC-GR-2
KPI GR 03	Accuracy metric for complex phasor voltage estimation (MaccV)	UC-GR-1; UC-GR-2
KPI GR 04	Convergence metric in terms of objective function	UC-GR-1; UC-GR-2
KPI GR 05	Convergence metric in terms of estimated voltage magnitude	UC-GR-1; UC-GR-2
KPI GR 06	Convergence metric in terms of estimated voltage angle	UC-GR-1; UC-GR-2
KPI GR EXTRA	Worst case coordinate error variance	UC-GR-1; UC-GR-2
KPI GR 07	Generation curtailment	UC-GR-3
KPI GR 08	Demand curtailment	UC-GR-3
KPI GR 09	Generation curtailment occurrences	UC-GR-3
KPI GR 10	Demand curtailment occurrences	UC-GR-3
KPI GR 11	Network limit violation occurrences	UC-GR-3
KPI GR 13	PMUs' field installation and integration	UC-GR-5
KPI GR 14	Data visualisation	UC-GR-5
KPI GR 15	Visualised tools and services	UC-GR-5

5.2.1 KPI_GR_01 Root Mean Square Error (RMSE)

KPI GR 01, Root Mean Square Error (RMSE), is a unitless metric for the evaluation of SE accuracy in terms of nodal voltage magnitudes. It captures the average 2-norm error in estimating the nodal voltage magnitudes. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{01}} = \sqrt{\sum_{i=1}^{n} \frac{(V_i^{true} - V_i^{est})^2}{n}}$$

where n is the number of network buses, V_i^{est} and V_i^{true} are respectively the estimated and true voltage magnitude of the i-th bus.

This metric was calculated for UC-GR-1 and UC-GR-2 by means of offline simulations. The desired value of this KPI, based on acceptable limits of voltage variation according to HEDNO Network Code which is ±5% of the nominal system voltage is set to be well below 0.01 p.u.

Thus, UC-GR-1 which aimed at the attainment of quality SE using accurate pseudo-measurements for observability purposes, yielded values of the KPI GR 01 between 0.05 and 0.1 p.u. These results are poor due to the limited actual measurements and the low measurement redundancy. On the other hand, the objective of UC-GR-2 was dedicated to the smooth integration of synchrophasor data into the SE tool, i.e., them being fused and co-processed with the pre-existing conventional measurements. The obtained values of the KPI GR 01 in this case were between 0.005 and 0.02 p.u. The obtained KPI results in UC-GR-2 were significantly better than the ones in UC-GR-1, getting closer to the accepted operation limits and could further be enhanced in case a systematic method for optimal placement of the related metering units (SMUs) was employed. Thus, taking that into account when the actual SMUs installations were to be realized during the fourth year of the project, the most appropriate nodes for installation of the SMUs were selected after analysis based on optimization techniques of the SE tool.

In conclusion, as anticipated, the integration of PMUs into the pre-existing metering infrastructure is highly beneficial for the accuracy of the estimated nodal voltage magnitudes. The improvement gets even more intense due to the low redundancy of pre-existing measurements processed in UC-GR-1. Concisely, the installation of SMUs, even in small numbers, can vitally improve the accuracy of estimated voltage magnitudes in a typical distribution network with a limited number of pre-existing conventional measurement data such as the Mesogeia pilot site.

Since a reference (true) state is needed for the computation of this KPI, it cannot be re-calculated during the demonstration of the SE tool.

5.2.2 KPI_GR_02 Relative Percentage Error (RPE)

Relative Percentage Error (RPE) is a unitless metric for the evaluation of SE accuracy in terms of nodal voltage magnitudes. It captures the relative error in estimating voltage magnitude per individual bus. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{02}} = \frac{V_i^{true} - V_i^{est}}{V_i^{true}} \times 100$$

where V_i^{est} and V_i^{true} are the estimated and true voltage magnitude of the i-th bus.

This metric was calculated for the two scenarios of UC-GR-1 and for UC-GR-2 by means of offline simulations. The desired value of this KPI, based on acceptable limits of voltage variation according to the HEDNO Network Code which is ±5% of the nominal system voltage is set to be well below 1%.

Thus, the obtained values of the KPI GR 02 for the UC-GR-1 were below 9%, with a mean value around 5%. These results are poor for the reasons described in subsection 5.2.1. On the other hand, the obtained values of the KPI GR 02 for UC-GR-2 were below 1%, with most of them being well below 1%. These results are excellent and can further be improved through optimal placement of SMUs. As mentioned in KPI GR 01, this finding was taken into consideration when the actual SMUs installations were to be realized during the fourth year of the project. Thus, the most appropriate nodes for installation of the SMUs were selected after analysis based on optimization techniques of the SE tool.

Similar to the case of KPI GR 01, the achieved values for KPI GR 02 in UC-GR-2 are considerably better compared to the ones in UC-GR-1. Therefore, the positive impact of the installation of SMUs, on the accuracy of estimated voltage magnitudes in the Mesogeia pilot site is also confirmed considering the KPI GR 02.

Since a reference (true) state is needed for the computation of the KPI, it cannot be re-calculated during the demonstration of the SE tool.

5.2.3 KPI_GR_03 Accuracy metric for complex phasor voltage estimation

KPI GR 03, M_{acc_V}, is a metric (measured in p.u.) for the evaluation of SE accuracy in terms of complex phasor voltages. It captures the effect of both nodal voltage magnitude and angle errors by combining them in a common 2-norm formula. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{03}} = \sqrt{\sum_{i=1}^{n} \left\| \tilde{V}_i^{true} - \tilde{V}_i^{est} \right\|^2}$$

where n is the number of the network buses, $\tilde{V}_i^{est}$ and $\tilde{V}_i^{true}$ are the estimated and true complex phasor voltage of the i-th bus.

This metric was calculated for UC-GR-1 and UC-GR-2 by means of offline simulations. The desired value of this KPI, based on the acceptable limits of voltage variation according to the HEDNO Network Code, which is ±5% of the nominal system voltage, is set to be below 0.2 p.u.

Thus, the acquired values of the KPI GR 03 for UC-GR-1 lay between 0.5 and 1.5 p.u, which are of low accuracy. Contrarily, the obtained values of the KPI GR 03 for UC-GR-2 were one order of magnitude smaller than 0.2 p.u. which indicate excellent SE accuracy.

The obtained KPI results in UC-GR-2 are substantially better than the ones in UC-GR-1. Hence, the integration of PMU data into the pre-existing measurement set leads to improved estimation of both nodal voltage magnitudes and phase angles, that is, nodal complex voltages. This improvement was to be expected since PMUs deliver measured phase angles, contrary to conventional metering systems, such as SCADA or smart metering units, which do not record voltage (or current) phase angles.

Since a reference (true) state is needed for the computation of the KPI, it cannot be re-calculated during the demonstration of the SE tool.

5.2.4 KPI_GR_04 Convergence metric in terms of objective function

KPI GR 04, $M_{conv_{obj}}$, is a unitless metric for the evaluation of the ability of the SE algorithm to converge to a solution. It quantifies the relative change in objective function which occurs at the final iteration. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{04}} = \left|1 - \frac{J^{kterm}}{J^{kterm-1}}\right|$$

where J is the value of the objective function and $kterm$ is the ascending number of the terminal iteration of the SE algorithm.

Since the KPI assesses the convergence quality, the target value for the relative change in the objective function which occurs at the final iteration is any value below 1. The closer to zero the value is, the better the convergence.

This metric was calculated for the UC-GR-1 and UC-GR-2 by means of offline simulations. The values of the KPI in both UCs were excellent (well below 1), thus, the SE tool exhibits an excellent behaviour in terms of the convergence metric related to the objective function of the solution algorithm.

5.2.5 KPI_GR_05 Convergence metric in terms of estimated voltage magnitude

KPI GR 05, M_{conv_V}, is a unitless metric for the evaluation of the ability of the SE algorithm to converge to a solution. It quantifies the maximum relative change in estimated voltage magnitudes which occurs at the final iteration. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{05}} = \max_i \left|1 - \frac{V_i^{kterm}}{V_i^{kterm-1}}\right|$$

where V_i is the voltage magnitude of the i-th bus and $kterm$ is the terminal iteration of the SE algorithm.

Since the KPI assesses the ability of the SE algorithm to converge to a solution in regards with the estimated voltage magnitudes, the desired value of this KPI is set to be below 0.002. Closer values to zero show more accuracy for the estimation of voltage magnitude estimate.

This metric was calculated for UC-GR-1 and UC-GR-2 by means of offline simulations. The values of the KPI in both UCs were excellent (well below 0.002), thus, the SE tool converges without problems to a solution given the pre-existing measurements as well as after the integration of PMU data. This finding confirms that the measurement weights were tuned appropriately. In general, numerical issues related to the operation of the SE tool can be addressed successfully in the presence of both highly accurate PMU data and less precise pseudo-measurements.

5.2.6 KPI_GR_06 Convergence metric in terms of estimated voltage angle

KPI GR 06, $M_{conv_{\delta}}$, is a metric (measured in degrees) for the evaluation of the ability of the SE algorithm to converge to a solution. It quantifies the maximum change in estimated voltage angles which occurs at the final iteration. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{06}} = \max_{i} \left| \theta_i^{kterm} - \theta_i^{kterm-1} \right|$$

where θ_i is the voltage angle of the i-th bus and $kterm$ is the ascending number of the terminal iteration of the SE algorithm.

Given that the KPI assesses the ability of the algorithm to converge to a solution in regards with voltage angles, the desired value of this KPI is set to be below 0.002 degrees.

This metric was calculated for the UC-GR-1 and UC-GR-2 by means of offline simulations. Similar to the case of KPI GR 05, the values of the KPI in both cases are excellent (well below 0.002 rad), thus, the convergence rate of the SE tool is high both before and after fusing the PMU data with the pre-existing measurements.

5.2.7 KPI_GR_EXTRA Worst case coordinate error variance

KPI GR EXTRA, Ψ_M, is a metric (measured in squared p.u.) for the evaluation of SE accuracy in terms of voltage magnitudes and angles. It is equal to the maximum diagonal entry of the state error covariance matrix. The covariance matrix identifies with the inverse of the gain matrix of the WLS model, which the SE tool is founded upon and detailed in D4.2.

This metric was calculated for the UC-GR-1 and UC-GR-2 via offline simulations. The baseline values of this KPI were determined based on the acceptable limits of voltage variation according to the HEDNO Network Code which is ±5% of the nominal system voltage. Thus, setting the $\pm 3\sigma$ range around a state estimate which follows the normal distribution equal to 0.01 p.u., the threshold value for the KPI, which is equal to σ^2, is approximately 3×10^{-6}.

In UC-GR-1, the acquired values of the KPI GR EXTRA were around 3×10^{-7}. These results are way below the threshold values, but the measurement weights strongly affect this KPI and, thus, its value is likely to be underestimated. The corresponding values obtained in UC-GR-2 were around 2×10^{-8}, which are well below the threshold and can further be improved if the SMUs are optimally allocated.

Given that no reference is needed in order to calculate this KPI, its importance is high to quantify the accuracy of the state estimates provided by the SE tool in real-time conditions. In both cases, the obtained KPI results were well below threshold values. Though, taking into account its strong dependence on the values of measurement weights, it is likely to be over- or underestimated in case simulated data are used. This is due to the fact that measurement weights are initially chosen and tuned to attain consistent algorithmic convergence, often, at the expense of precise quantification of measurement error variances. This is a plausible explanation for the good KPI values in UC-GR-1, contrarily to the metrics KPI GR 01, 02 and 03.

5.2.8 KPI_GR_07 Generation curtailment

KPI GR 07, ΔC_{RES}, is a unitless metric that compares the amount of energy from RES that is not injected to the grid (even though it is available) due to operational limits of the grid, between the Variable Network Tariff scenario and the BaU scenario. The formula used to calculate this KPI is as follows:

$$KPI_{GR_{07}} = \frac{\sum_{t\in T}\sum_{i\in I} E_{g_{i,t}}^{BaU} - \sum_{t\in T}\sum_{i\in I} E_{g_{i,t}}^{R\&I}}{\sum_{t\in T}\sum_{i\in I} E_{g_{i,t}}^{BaU}} \times 100$$

where $E_{g_{i,t}}^{BaU}$ is the energy curtailment of the i-th RES facility at period t in the BaU – Flat Network Tariff scenario (kWh), $E_{g_{i,t}}^{R\&I}$ is the energy curtailment of the i-th RES facility at period t in the Variable Network Tariff scenario (kWh), I is the set of RES facilities under consideration, and T is the set of time intervals of the period under consideration (excluding periods of scheduled maintenance and outages). Thus, the higher the value of this KPI the better, with 100% meaning that no generation curtailment actions are needed.

A variable DUoS tariff could potentially resolve all cases, which would theoretically mean that no RES generation curtailment would be needed at all, if it were a true locational marginal price. However, since the network tariff is subject to regulatory constraints and there are technical constraints regarding the efficient network use, the reduction of RES generation curtailment is expected to be 20% or above.

This metric was calculated for UC-GR-3 and UC-GR-4. Historical, actual measurement data were clustered in 4 day-types, representing 4 distinct tariff patterns (one for each day-type). Following the design phase which generates the DUoS tariff patterns for the entire year, the validation phase is executed where three distinct cases are tested on actual network conditions during daily operation. The first case, known as BaU scenario with flat network tariffs demonstrates 0% efficiency since no flexibility is motivated. The second case applies the proposed framework and the variable DUoS tariffs (hourly, hourly-loc) derived from the design phase. The third case refers to the theoretical optimal scenario where the DSO controls all available flexibility and has perfect knowledge, thus the efficiency is 100%. Therefore, the amount of RES generation curtailed in kWh is compared to the first and the third case. The results for UC-GR-3 were calculated as 3% for Hourly network tariff and 6% for Hourly-Loc network tariff, both of which are well below the target value.

KPI values regarding generation curtailment are relatively low, due to the nature of the simulated topology and the cost of generation curtailment compared to demand curtailment. The algorithm prioritizes demand curtailment reduction due to its higher cost when such actions take place. Therefore, it is expected that generation curtailment reduction is relatively low.

5.2.9 KPI_GR_08 Demand curtailment

KPI GR 08, ΔC_{DEM}, is a unitless metric that compares the amount of energy consumption that needs to be curtailed due to operational limits of the grid, between the Variable Network Tariff and the BaU scenario. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{08}} = \frac{\sum_{t\in T}\sum_{i\in I} E_{d_{i,t}}^{BaU} - \sum_{t\in T}\sum_{i\in I} E_{d_{i,t}}^{R\&I}}{\sum_{t\in T}\sum_{i\in I} E_{d_{i,t}}^{BaU}} \times 100$$

where $E_{d_{i,t}}^{BaU}$ is the demand curtailment of the i-th flexible customer facility at period t in the BaU – Flat Network Tariff scenario (kWh), $E_{d_{i,t}}^{R\&I}$ is the demand curtailment of the i-th flexible customer facility at period t in the Variable Network Tariff scenario (kWh), I is the set of flexible customers under consideration, and T is the set of time intervals of the period under consideration. Thus, the higher the value of this KPI the better, with 100% meaning that no demand curtailment actions are needed.

A variable network tariff could potentially resolve all cases, which would theoretically mean that no demand curtailment would be needed at all, if it were a true locational marginal price. However, since the network tariff is subject to regulatory constraints and there are technical constraints regarding the efficient network use, the reduction of demand curtailment is expected to be 20% or above.

This metric was calculated for UC-GR-3 and UC-GR-4. The same validation framework as presented in section 5.2.8 was implemented for the calculation of this KPI. The variable DUoS tariffs (hourly, hourly-loc) scenario showcased 60% demand curtailment for the Hourly network tariff and 68% for the Hourly-Loc network tariff.

Both KPI values for the Hourly and Hourly-Loc scheme are well above the target value, namely 20% as set in D4.1. Thus, KPI values are excellent for UC-GR-3. Hourly-Loc network tariff has better efficiency than Hourly network tariff due to its spatial granularity. Comparing generation and demand curtailment a big difference is observed between KPI GR 07 and KPI GR 08. The difference in the performance of the two KPIs is due to the demand curtailment penalty being much higher than the generation curtailment penalty and therefore, leading in the optimal solution demand curtailment reduction always being prioritised over generation curtailment. If a different (higher) generation curtailment penalty was preferred, then generation curtailment reduction (%) would be also higher.

5.2.10 KPI_GR_09 Generation curtailment occurrences

KPI GR 09, $\Delta N_{C_{RES}}$, is a unitless metric that compares the number of occurrences of generation curtailment for the mitigation of network limit violations between the Variable Network Tariff scenario and the BaU scenario. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{09}} = \frac{N_{C_{RES}}^{BaU} - N_{C_{RES}}^{R\&I}}{N_{C_{RES}}^{BaU}} \times 100$$

where $N_{C_{RES}} = \sum_{t \in T} k_t$ is the number of occurrences of RES generation curtailment, k_t is a binary variable indicating whether generation curtailment occurred anywhere in the network at period t, T is the set of time intervals of period under consideration, $N_{C_{RES}}^{BaU}$ is the number of occurrences of RES generation curtailment in BaU – Flatt Network Tariff scenario, and $N_{C_{RES}}^{R\&I}$ is the number of occurrences of RES generation curtailment in Variable Network Tariff scenario. Thus, the higher the value of this KPI the better, with 100% meaning that no generation curtailment actions occurred.

A variable network tariff could potentially resolve all cases, which would theoretically mean that no RES generation curtailment would be needed at all. However, since the network tariff is subject to regulatory constraints and there are technical constraints regarding the efficient network use, the reduction of RES generation curtailment occurrences is expected to be 20% or above.

This metric was calculated for UC-GR-3 and UC-GR-4. The same validation framework as presented in section 5.2.8 was implemented for the calculation of this KPI. The variable DUoS tariffs (hourly, hourly-loc) scenario showcased 3% decrease of generation curtailment occurrences for the Hourly network tariff and 5% decrease for the Hourly-Loc network tariff.

Both KPI values regarding generation curtailment occurrences are relatively low and well below the target value for the same reasons mentioned in section 5.2.8.

5.2.11 KPI_GR_10 Demand curtailment occurrences

KPI GR 10, $\Delta N_{C_{DEMAND}}$, is a unitless metric that compares the number of occurrences of demand curtailment for the mitigation of network limit violations between the Variable Network Tariff scenario and the BaU scenario. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{10}} = \frac{N_{C_{DEMAND}}^{BaU} - N_{C_{DEMAND}}^{R\&I}}{N_{C_{DEMAND}}^{BaU}} \times 100$$

where $N_{C_{DEMAND}} = \sum_{t \in T} m_t$ is the number of occurrences of demand curtailment, m_t is a binary variable indicating whether demand curtailment occurred anywhere in the network at period t, T is the set of time intervals of period under consideration, $N_{C_{DEMAND}}^{BaU}$ is the number of occurrences of demand curtailment in BaU – Flatt Network Tariff scenario and $N_{C_{DEMAND}}^{R\&I}$ is the number of occurrences of demand curtailment in Variable Network Tariff scenario. Thus, the higher the value of this KPI the better, with 100% meaning that no demand curtailment actions occurred.

A variable network tariff could potentially resolve all cases, which would theoretically mean that no demand curtailment would be needed at all. However, since the network tariff is subject to regulatory constraints and there are technical constraints regarding the efficient network use, the reduction of demand curtailment occurrences is expected to be 20% or above.

This metric was calculated for UC-GR-3 and UC-GR-4. The same validation framework as presented in section 5.2.8 was implemented for the calculation of this KPI. The variable DUoS tariffs (hourly, hourly-loc) scenario showcased 24% decrease of demand curtailment occurrences for the Hourly network tariff and 30% decrease for the Hourly-Loc network tariff.

Both KPI values are slightly above the minimum threshold percentage. Hourly-Loc network tariff has better efficiency than Hourly network tariff due to its spatial granularity.

5.2.12 KPI_GR_11 Network limit violation occurrences

KPI GR 11, NV, is unitless metric that quantifies the difference between the number of network limit violation occurrences under a 24-hour timeframe in the Variable Network Tariff scenario and the equivalent one in the BaU scenario. The formula used to calculate the KPI is as follows:

$$KPI_{GR_{11}} = \frac{N_{total_{violations}}^{BaU} - N_{total_{violations}}^{R\&I}}{N_{total_{violations}}^{BaU}} \times 100$$

where $N_{total_{violations}}^{BaU} = N_{RES}^{BaU} \cup N_{demand}^{BaU}$ is the total number of network limit violation occurrences in BaU – Flat Network Tariff scenario, $N_{total_{violations}}^{R\&I} = N_{RES}^{R\&I} \cup N_{demand}^{R\&I}$ is the total number of network limit violation occurrences in Variable Network Tariff scenario, $N_{C_{RES}}$ is the number of occurrences of RES generation curtailment and $N_{C_{demand}}$ is the number of occurrences of demand curtailment. Thus, the higher the value of this KPI the better, with 100% meaning that no generation or demand curtailment actions occurred.

The use of variable network tariff instead of flat network tariff by the DSO will incentivise certain behaviours from the DERs' owners, which will lead to an optimal dispatch with the least possible network limit violations. Since the network tariff is subject to regulatory constraints and there are technical constraints regarding the secure and efficient network use, the reduction of network limit violations is expected to be 20% or above.

This metric was calculated for UC-GR-3 and UC-GR-4. The same validation framework as presented in section 5.2.8 was implemented for the calculation of this KPI. The variable DUoS tariffs (hourly, hourly-loc) scenario showcased 18% decrease of network limit violation occurrences for the Hourly network tariff and 23% decrease for the Hourly-Loc network tariff. A limit violation occurrence is equivalent to a generation and/or demand curtailment occurrence as every time a limit violation is bound to happen, curtailment is decided to prevent it.

KPI value calculated using Hourly network tariff is just below the minimum threshold value, while KPI value calculated using Hourly-Loc network tariff is just above 20%. Hourly-Loc network tariff has better efficiency than Hourly network tariff due to its spatial granularity.

5.2.13 KPI_GR_13 PMUs' field installation and integration

KPI GR 13, indicates the number of PMUs actually installed in the field and integrated in the DSO Technical Platform.

A study of the international literature on the optimal trade-off between the benefits of PMUs and the implications caused by the development of a PMU-based infrastructure from scratch, led us to set the target value of five PMUs. In this regard, a thorough investigation of the Mesogeia pilot site has been conducted to identify the candidate locations for PMU installation considering the pre-existing metering equipment that can be exploited for PMU integration.

This goal was successfully achieved at the end of the project as all five PMUs received from RWTH were installed in five different substations of feeder P210 which were selected to facilitate the optimization of the SE tool's performance. Additionally, through cooperation with RWTH, which originally receives the PMU data, a private MQTT broker was used for data publication. HEDNO was then able to subscribe to that broker, retrieve the data and store them in the DSO Data Server. Also, the data are provided to the Platone DSOTP where the data from all five PMUs (voltage and current phasors) are depicted in real time.

The simulation results in D4.2 assuming a number of twenty installed PMUs indicated a significant improvement in SE accuracy. In this context, the installation of five PMUs has a lower but still appreciable impact on the quality of the SE tool. Actually, the reduced number of placed PMUs mitigates the technical complexities and the costs associated with the development of the required infrastructure.

5.2.14 KPI_GR_14 Data visualisation

KPI GR 14 indicates the number of data sources (e.g., AMR, GIS, SCADA-DMS, DSO Data Server) that are visualised in the DSO Technical Platform.

In order to quantify this KPI, data from any HEDNO data source (e.g., AMR, GIS, SCADA-DMS, DSO data server) that is successfully visualized in the DSOTP is counted. The desired value for this KPI is four, as the data from four different data sources are required to test the tools and services developed within the Platone Open Framework for the Greek demo.

All of the aforementioned data sources were successfully displayed in the final version of the UI that was developed by WP2 specifically for the Greek demo and integrated in the DSOTP that was deployed within the cloud infrastructure of HEDNO. The successful data visualisation provides several advantages for the Greek DSO. A real-time state of the network in the form of a topology is available, along with the set of measurements that are fed in the SE tool comprising of the HV-MV data, the smart meters data from the MV customers, and the PMU data. This provides advanced observability for the operator of the system achieving an optimised grid operation.

Figure 39 below shows graphs of the voltage magnitude and angle of a selected-by-the-user bus of the test site as dispayed in the the UI dashboard. Figure 40 demonstrates the real against the estimated active power injection for the same node of the network.

Figure 39 Bus voltage magnitude and angle.

Figure 40 Active power injection (real with yellow and estimated with green).

5.2.15 KPI_GR_15 Visualised tools and services

KPI GR 15, indicates the number of tools and services which are visualised in the DSOTP. The outputs of such visualised services allow the DSO to operate the distribution network more efficiently. The integration of these visualised tools and services has been a great success for the Greek demo, as now these tools can be considered as new add-ons in hands of the DSO for the day-to-day operation of the grid.

The desired value for this KPI was originally three referring to the number of tools and services aimed to be developed within the Greek demo: the SE tool [10], the algorithm for optimal DER control [3], and the algorithm for ancillary services [2]. However, the algorithm for ancillary services was not eventually accompanied by a different tool with different type of results to be shown. Instead, it was considered as an extension of the algorithm for optimal DER control. Thus, in the UI developed there are two modes ('State Estimation Results' and 'Tariff information') providing the user with interesting information about the status of the grid.

In the 'State Estimation Results' mode, the SE tool's results (voltage magnitude, voltage angle, estimated active and reactive power injection) for all the nodes of the pilot site network (lines P210, P490) can be seen near real-time with data being updated every 15 minutes (Figure 41Figure 38). Also, the actual measured active and reactive power injection per node are provided.

Colour coding was developed to allow the user understand at a glance the grid conditions in terms of voltage levels. The green colour indicates 'healthy' nodes, while the amber nodes show parts of the network where voltage is above or below 3.5% of the nominal, but still within the range of +/-5%. If the voltage is out of the +/-5% range, the node turns red to underline that a network limit violation occurs.

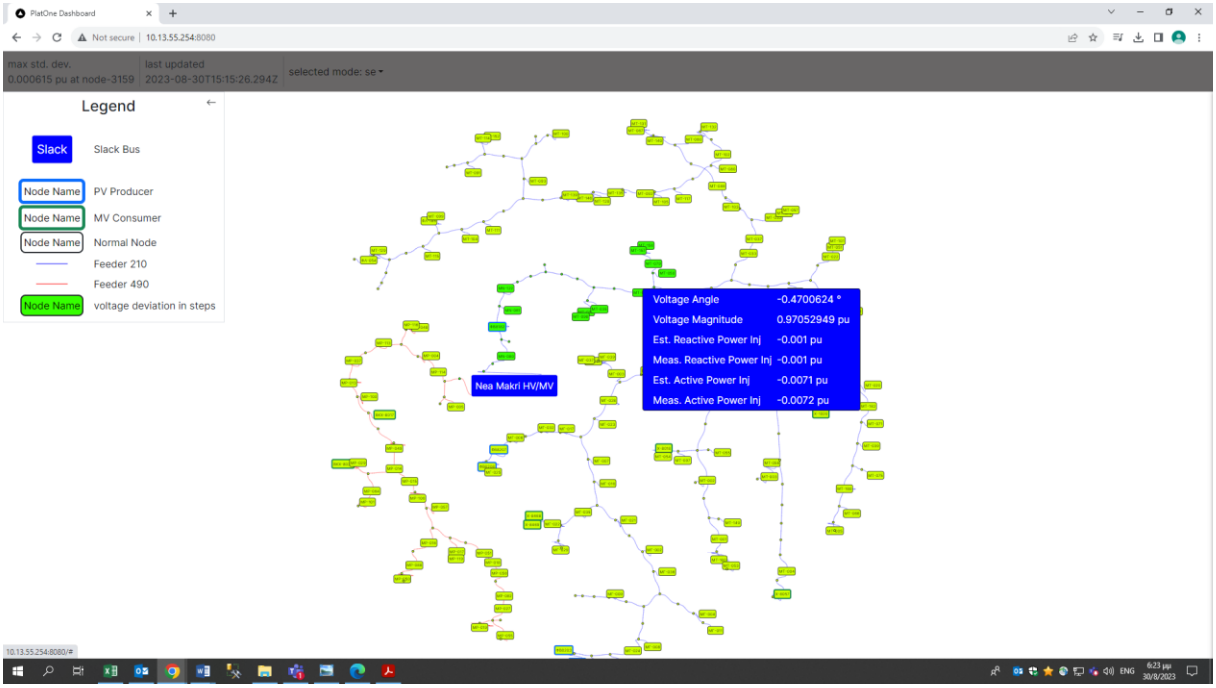


Figure 41: 'State Estimation Results' mode (screenshot).

In the 'Tariff information' mode (Figure 42Figure 38), the DUoS tariff per node can be seen. The tariff considers the topology as well as the day type that the user (operator) chooses from a drop-down menu at the top.

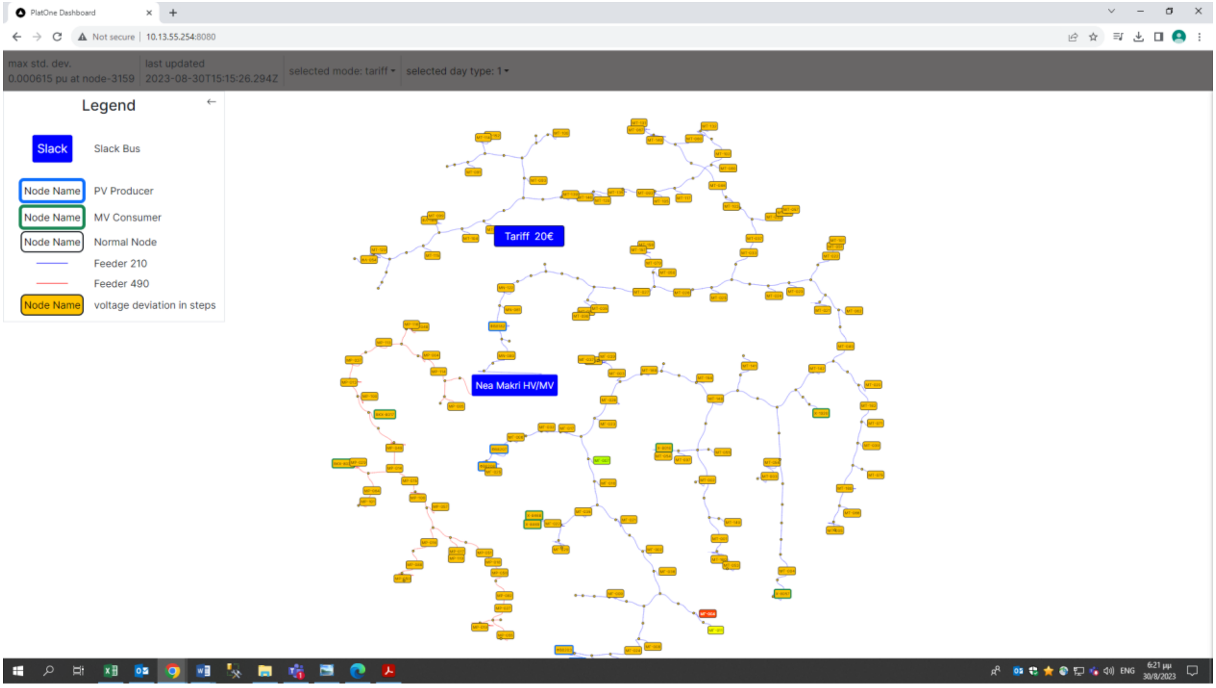


Figure 42: 'Tariff information' mode (screenshot).

Finally, the Greek demo decided to visualise the KPI GR EXTRA (Worst case coordinate error variance) as a metric for the user to evaluate the accuracy of the estimated state of the grid that he/she is looking at. Worst case coordinate error variance is calculated every 15 min along with the SE tool's run to provide the estimate of the network state (Figure 43).

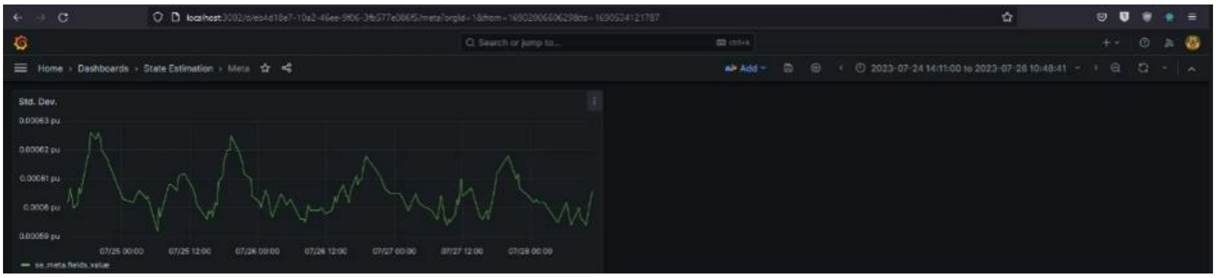


Figure 43: KPI GR EXTRA visualization in the DSOTP.

6 Customer Engagement

The Platone project envisages stakeholders as active participants capable of providing flexibility to the grid. Therefore, a primary objective of the customer engagement methodologies was to adopt a user-centric approach, aiming to inform the relevant stakeholders about the innovative solutions of the Greek demo and motivate their involvement in future flexibility markets. However, at the moment in Greece there is no regulatory framework for provision of flexibility services through a variable DUoS tariffs scheme. Hence, this specific Greek demo solution could not be verified in a real-life environment. Even though the UCs examined could not be tested with actual participants, various methods were developed so that the potential future customers become aware of the method and get deeper knowledge of distribution network operation and flexibility services themselves.

With the scope of familiarising potential participants with future energy flexibility schemes, the Greek demo organised a series of dissemination events. The main goal of these events was to inform the relevant stakeholders about the Platone architecture and the context of the Greek demo, conveying the benefits and value of the Greek demo's innovative solutions, namely the variable DUoS tariff model and the SE tool. By highlighting the advantages and positive outcomes of the proposed solutions, the project sought to capture the attention and engagement of interested stakeholders.

Three workshops were held, with some of them benefitting by the participation of other Horizon 2020 projects as well. During these workshops, representatives from diverse sectors, including industry, academia, research, the energy sector, local municipalities, and key entities such as the Greek DSO (HEDNO) and TSO (IPTO), were actively involved. The workshops served as a platform to raise awareness about not only the Greek demo, but also the Platone project and its concept as a whole, reaching out to all relevant stakeholders.

A core proposal developed by the Greek demo within Platone was the use of algorithmically designed variable DUoS tariffs, which aimed to activate flexible load shifting for the efficient operation of the distribution network. However, as already mentioned, since DUoS tariffs are regulated by the National Regulatory Authority (NRA) of Greece and at the moment there is no provision for variable DUoS tariffs schemes, conducting a real-life test of the solution with active customer participation was not feasible. In response to this limitation, the Greek demo took a proactive approach and designed an informative questionnaire to share with respondents from various sectors (e.g., the energy sector, academia, NRA, potential customers etc.,), aiming to inform them about the innovative approach of the variable DUoS tariffs and provide them with a clear understanding of its principles and benefits. In essence, this questionnaire was designed and shared in order to gather information about the public's willingness to modify their energy consumption patterns in a hypothetical scenario where the variable DUoS tariffs were applied. In summary, this questionnaire served as a vital tool in gathering public opinions and assessing the potential viability and acceptance of the variable DUoS tariffs approach, providing essential insights for further developments in the field of flexibility markets and services.

The customer engagement activities organized and developed within the Greek demo are summarised below in chronological order:

- 'Platone Engagement Workshop', February 18th, 2021
- Platone Open Day 'Innovation for flexibility', November 24th, 2021
- 1st Research Projects Dissemination Event, December 21st, 2022
- Questionnaire regarding stakeholders' potential participation in flexibility markets, June 21st, 2023
- Study tour for the Greek demo, June 30th, 2023

A more detailed description of the aforementioned activities can be found in reports D4.6 [11] and D1.5 [12].

Reflecting on insights and knowledge gained from the customer engagement activities during the four-year duration of Platone, several key points emerge:

- Significant interest is expressed by all stakeholders in the energy sector as evidenced by the strong participation at the workshops on the innovation that research projects like Platone propose for the future of distribution grids.

- There is keen interest in the technical aspects of Platone, particularly regarding the PMUs and the advantages they offer to the grid. This indicates a recognition of the importance of advanced grid monitoring technologies.
- A properly designed questionnaire can become an effective survey tool to receive constructive feedback in innovative solutions that cannot be tested in real-life.
- The user-engagement questionnaire results reveal that customers are willing to participate in the flexibility market especially when financial incentives are involved. However, it is crucial to provide them with adequate information to help them make decisions and eventually and confidently engage in flexibility provision by modifying their consumption patterns.

Overall, the customer engagement activities have highlighted the enthusiasm and interest among stakeholders in the energy sector as well as the importance of providing clear information and appropriate incentives to encourage customers' active participation in flexibility markets. These insights can guide future developments and improvements in the implementation of projects similar to Platone, and they can also be taken into consideration in any future consultations on flexibility markets, flexibility services, and variable DUoS tariffs design.

For a comprehensive understanding of the customer engagement methodologies and outcomes of the dissemination events, please refer to D4.6 "Report on lessons learned on customer engagement methodologies." This report delves deeper into the insights gained and provides valuable information for future customer engagement activities in the field of energy flexibility pilots.

7 Conclusion

As Platone comes to its close, several important conclusions can be drawn from the four-year duration of the project. Platone introduces a groundbreaking concept for modern DSOs: a modular, customizable framework, known as the Platone Open Framework. This framework integrates diverse platforms, accommodating both existing metering and grid monitoring systems, as well as novel tools and infrastructure with the primary purpose to facilitate the development of customer-centric services. The successful testing of the Platone Open Framework within the Greek demo showcases its effectiveness. By leveraging its BAL and DSOTP, the Greek DSO (HEDNO) has successfully established a completely new, integral and valuable IT environment. Notably, HEDNO, has already fully incorporated innovative tools and services into this environment, with the potential to host many more in the future. This has been made possible by the framework's inherent openness and modular design, offering an opportunity for future advancements and innovations.

During the process of adopting the Platone Open Framework, the Greek demo developed its own new tools: the SE tool and the variable DUoS tariffs design tool for the optimal DER control. Additionally, the installation PMUs was completed for both SE and grid monitoring purposes. While SE techniques and PMUs are used widely on transmission networks, their application on the distribution networks is relatively limited. Hence, the fact that within the context of Platone an application such as the SE tool was deployed for the first time by the Greek DSO, marks a great success for the Greek demo. The SE tool as tested in the Greek demo, performed well in delivering estimates with good accuracy of all power injections at terminal transformers of the examined topology, and proved that the integration of PMUs into the pre-existing metering infrastructure is highly beneficial for the accuracy of the estimated grid state. Among its core functionality, SE tool acted also as a key enabler for harvesting flexibility since it provided the necessary input for the variable DUoS tariffs design tool that was developed in the Greek demo.

The implementation of the algorithm for optimal DER control, i.e. the proposed variable DUoS tariff design, showed that significant benefits can be leveraged by utilizing variable DUoS tariffs to harness flexibility from consumers. This advantage was evident in the context of both Day-Ahead market and in Real-Time scenarios (e.g. frequency support request from the TSO). Also, it was demonstrated that even a small clustering (4-day types) captures sufficiently the variability of the grid conditions leading to an efficacious variable DUoS tariffs design. The designed tariffs proved effective in incentivising load shifting by the consumers/prosumers of the test grid, so that potential network limit violations occurrences get avoided and any mitigation actions (generation/demand curtailment) that the DSO would typically take, get reduced. Finally, it’s important to note that the Greek demo verified the efficiency of the joint use of SE tool and the algorithm for optimal DER control.

The Platone Greek demo can confidently claim that they completed the installation of PMUs for the first time in the Hellenic distribution grids, this representing another major achievement. The data obtained from these PMUs serves as valuable measurements input for the SE tool enhancing its output accuracy. Additionally, the devices themselves will be further used as grid monitoring equipment by HEDNO. Various technical issues arose during the actual PMUs’ commissioning procedure, which were successfully tackled, but revealed that a large-scale deployment of the device at its current version would present difficulties for a DSO with the size of HEDNO. The additional external sensors that were needed for the field application of the PMUs raised concerns about the accuracy of the measurements and underlined that the equipment is not a plug-and-play solution, which would significantly simplify the installation process. In terms of weathering the climate of the Mediterranean, the operation of the PMUs did not appear to have been impacted by the high temperatures of the Greek summer.

A key part of the project’s evolution has been the dissemination of the objectives that Platone represents in general, as well as the Greek demo in specific. Through a series of workshops and events, many of which realized in a hybrid format due to Covid-19 restrictions, the Greek demo team effectively communicated the message of the project to diverse audiences, including with participants from various backgrounds (e.g. energy sector, academia, businesses etc.). In these events, the team also presented key findings of the Greek pilot project. In order to gauge the willingness of the general public to respond to future variable DUoS tariffs scheme as the one conceptualised by the Greek demo, a dedicated questionnaire was designed and circulated via email, yielding highly informative results, further discussed in deliverable D4.6.

Concluding, the overall experience and meaningful results derived from the Platone Greek demo provide a foundation upon which, similar initiatives within the evolving energy sector can be developed. The main findings of the Platone project could also be taken under consideration in case of future regulatory changes such as the proposed variable DUoS tariffs scheme. Additionally, these findings can lead to informed strategic decisions for HEDNO, including the potential for large-scale installation of PMUs and the integration of SE for day-to-day grid monitoring and grid management operations.

8 List of Tables

9 List of Figures

10 List of References

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11 List of Abbreviations

Abbreviation	Term
AMR	Automatic Meter Reading
API	Application Program Interface
BAL	Blockchain Access Layer
BAP	Blockchain Access Platform
BaU	Business-as-Usual
CIM	Common Information Model
DA	Day-Ahead
DER	Distributed Energy Resource
DSO	Distribution System Operator
DSOTP	Distribution System Operator Technical Platform
DUoS	Distribution Use-of-System
EV	Electric Vehicle
GIS	Geographic Information System
GPS	Global Positioning System
GSM	Global System for Mobile communication
HV	High Voltage
KKT	Karush-Kuhn-Tucker
KPI	Key Performance Indicator
LV	Low Voltage
MP	Market Platform
MQTT	Message Queue Telemetry Transport
MV	Medium Voltage
NRA	National Regulatory Authority
OPF	Optimal Power Flow
PMU	Phasor Measurement Unit
PSS/E	Power System Simulation for Engineering
PV	Photovoltaic
RES	Renewable Energy Sources
RT	Real-Time
SCADA-DMS	Supervisory Control And Data Acquisition - Distribution Management System
SCD	Shared Customer Database
SE	State Estimation
SMU	Synchronized Measurement Unit
TRL	Technology Readiness Level
TSO	Transmission System Operator
UC	Use Case

UI	User Interface
VM	Virtual Machine
WLS	Weighted Least Squares
XML	Extensible Markup Language

Annex A Data Converter for State Estimation tool

As part of the implementation of the SE tool in the Greek demo, the development of data and file converters was required. The need for these two converters was not clear from the beginning of the Platone project, but it was an essential part for the implementation and the final integration of the SE tool in the DSOTP. The data of the Greek demo's electricity distribution network topologies, as well as the real time measurements (Prosumers' active and reactive power, voltages, currents), are stored by using the CIM format. However, the SE tool takes input files that are stored in another type of format (PTI format). Therefore, for the data required by the SE tool to be readable, the use of intermediate converters is required, which adapt the various data according to the requirements of the SE tool. The data fed into the SE tool is divided into two types. The first type of data refers to the distribution network topologies. This data includes the types of network lines, the locations of buses and the locations of prosumers. The second type of data contains measurements, which are taken from the various network assets in real time. Below is a brief description of the input XML files that are processed by the two converters. The topology converter produces a .sys file in PTI format that is given as input to the SE tool, along with the .ses file, also in PTI format, produced by the measurement converter. The two converters have been developed in Python programming languages (Figure 44).

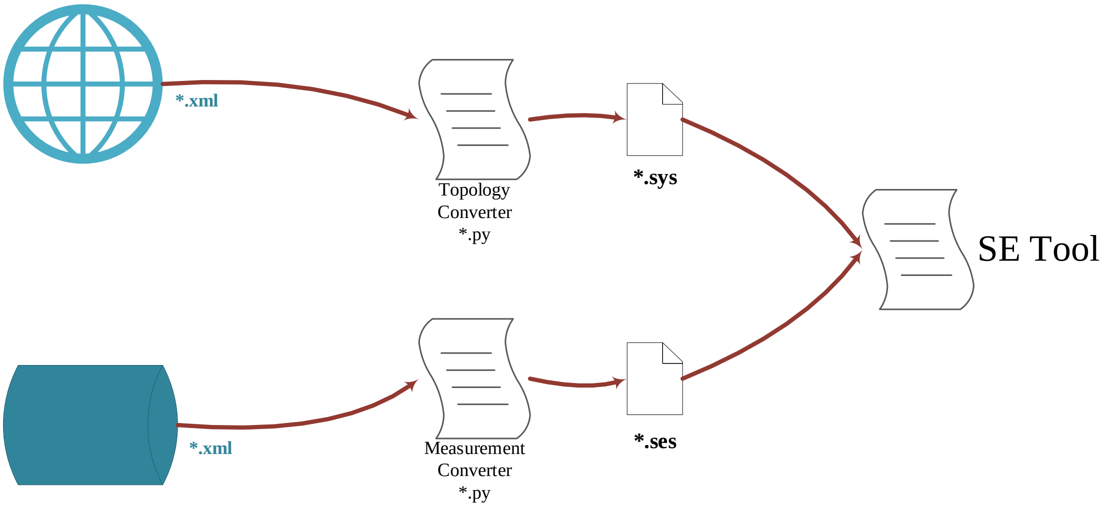

Figure 44: Flow diagram of the CIM2PTI conversion.

A.1 Network topology conversion

The attributes contained in the XML file, used to create the files of the corresponding Greek demo topologies are of three types. The first type of attributes includes the buses of the system, which are presented as topological nodes. Each topological node contains one or more terminals. Terminals are electrical connection points to a piece of conducting equipment, like line segments and switches. Therefore, attributes "terminal" corresponds to a specific topological node. The structure of the "topologicalnode" and the "terminal" attributes are depicted in Figure 45 and Figure 46**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, respectively. Moreover, the fixed produced/consumed power of each bus included is defined by using the "energyconsumer" attributes (Figure 47). Terminals include an attribute, called "conductingequipment", which is an RFD, referring to the AC line segments of the network (Figure 48).

The above logic, on which the structure of the CIM files is based, results in a sequence between the scales and the corresponding lines connecting them. Therefore, based on this logic, the topology converter has been implemented, to interpret the data of the CIM files and therefore, to convert this data into PTI format.

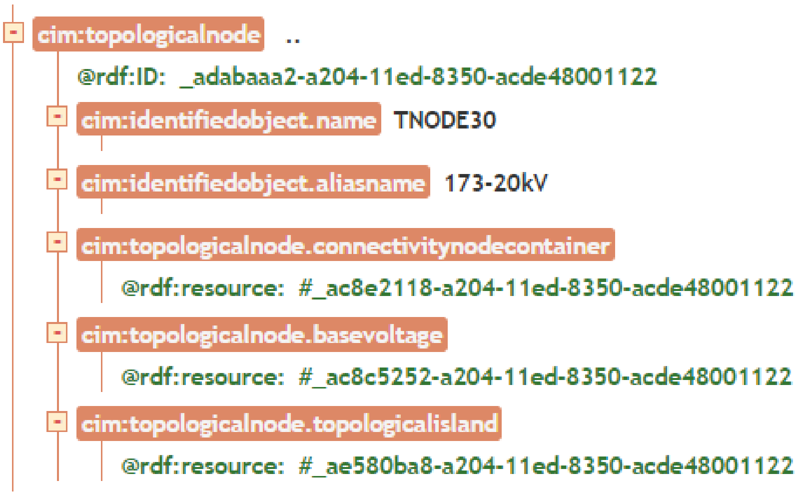

Figure 45: Structure of topological node attributes.

Figure 46: Structure of terminal attributes.

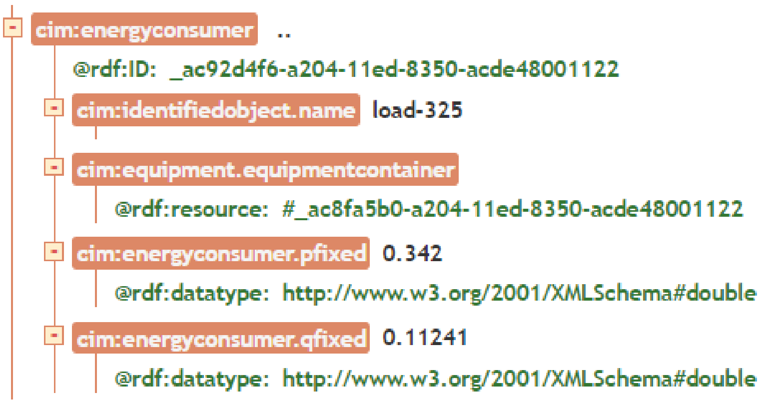

Figure 47: Structure of energy consumer attributes.

Figure 48: Structure of AC line segment attributes.

However, the topology converter, which is developed in Python language, is simplified, to reduce the computational time of the conversion. This is achieved by using the identifiedobject.name attributes of the “aclinesegment” attributes and the identifiedobject.name of the “energyconsumer” attribute. This is possible since the names of these objects contain the names of the buses of the topologies which are considered in the Greek demo.

A.2 Measurement conversion

The measurements are taken in real time, and stored into XML format, according to the CIM standard. An indicative snapshot of the structure of XML files of this type are shown in Figure 49. All the aggregated data from the pre-existing metering infrastructures (SCADA, AMR) and the newly installed SMUs are synchronised and combined into a unified XML file within the DSO Data Server. This file is subsequently fed into the measurement converter for further processing.

For each attribute “metereading”, the number of the meter to which it corresponds, the measurements it contains, and the corresponding measurement codes are read. After that, for each measurement included in each “metereading”, its type is checked through the measurement code received.

Figure 49: Attributes of meter readings XML file, based on CIM format.