Development and Implementation of the “ABCM” platform

D8.3

Authors:

Markos Asprou (UCY)

Lenos Hadjidemetriou (UCY)

Charalambos Charalambous (UCY)

Kyriakos Kyriakou (UCY)

Therapontos Fivos (EAC)

Michalis Michael (CTSO)

Rogiros Tapakis (CTSO)

Responsible Partner	University of Cyprus
Checked by WP leader	Emmanouil Zoulias (UoA), 28/9/2023
Verified by the appointed Reviewers	Maria Papademetriou (CINTECH), 14/9/2023 Anastasis Tzoumpas (UBITECH ENERGY), 13/9/2023
Approved by Project Coordinator	Padraic McKeever (Fraunhofer), 29/9/2023

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About OneNet

The project OneNet (One Network for Europe) will provide a seamless integration of all the actors in the electricity network across Europe to create the conditions for a synergistic operation that optimizes the overall energy system while creating an open and fair market structure.

OneNet is funded through the EU's eighth Framework Programme Horizon 2020, "TSO – DSO Consumer: Large-scale demonstrations of innovative grid services through demand response, storage and small-scale (RES) generation" and responds to the call "Building a low-carbon, climate resilient future (LC)".

As the electrical grid moves from being a fully centralized to a highly decentralized system, grid operators have to adapt to this changing environment and adjust their current business model to accommodate faster reactions and adaptive flexibility. This is an unprecedented challenge requiring an unprecedented solution. The project brings together a consortium of over seventy partners, including key IT players, leading research institutions and the two most relevant associations for grid operators.

The key elements of the project are:

1. Definition of a common market design for Europe: this means standardized products and key parameters for grid services which aim at the coordination of all actors, from grid operators to customers;
2. Definition of a Common IT Architecture and Common IT Interfaces: this means not trying to create a single IT platform for all the products but enabling an open architecture of interactions among several platforms so that anybody can join any market across Europe; and
3. Large-scale demonstrators to implement and showcase the scalable solutions developed throughout the project. These demonstrators are organized in four clusters coming to include countries in every region of Europe and testing innovative use cases never validated before.

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Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957739

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957739

List of Figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957739

List of Abbreviations and Acronyms

Acronym	Meaning
ABCM-D	Active Balancing Congestion Management-DSO
ABCM-T	Active Balancing Congestion Management-TSO
API	Application Programming Interface
BESS	Battery Energy Storage System
BSP	Balancing Service Provider
BUC	Business Use Cases
DER	Distributed Energy Resources
DSO	Distribution System Operator
EAC	Electricity Authority of Cyprus
EMT	Electromagnetic Transients
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FSP	Flexibility Service Provider
GUI	Graphical User Interface
HiL	Hardware in the Loop
HMI	Human Machine Interface
HV	High Voltage
ICT	Information and Communication Technology
ID	Identification number
KPI	Key performance Indicator
LV	Low Voltage
MV	Medium Voltage
PB	Phase Balancing
PDC	Phasor Data Concentrator
PF	Power Factor
PMU	Phasor Measurement Unit
PV	Photovoltaic
RES	Renewable Energy Sources
RTS	Real Time Simulator
SCADA	Supervisory Control and Data Acquisition
SUC	System Use Cases
TRL	Technology Readiness Level
TSO	Transmission System Operator
TSR	Trading and Settlement Rules

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Executive Summary

This deliverable presents a comprehensive overview of the Cyprus demo implementation within the OneNet project. The Cyprus demo primarily addresses the challenges encountered by the islanded Cyprus power grid in coping with the high penetration of RES. The document describes in detail the development of critical components to showcase how the challenges of the Cyprus power system can be overcome through the innovative solutions proposed in the Cyprus demo. The key highlights of the deliverable are:

1. **Development of the Cyprus digital twin:** The heart of the Cyprus demo is the Cyprus power system digital twin which is a pivotal element for testing extreme scenarios in the Cyprus power system, while safeguarding the real power infrastructure. In this direction, the Cyprus digital twin was developed in a real time simulation environment, and it includes the full transmission level, and a part of the medium and low voltage distribution grid. A multi-step procedure was followed in the development of the Cyprus power system digital twin that includes the modelling of the grid in Simulink environment, the development of and inclusion of smart inverters models in the grid model, the integration of field measurements in order to represent the actual operating conditions to the grid, and the creation of a power and control HiL environment that enables the integration of the ABCM platforms and other measuring and grid elements such as PMUs and BSS. The Cyprus digital twin runs in the real time simulator successfully and is able to represent adequately the actual conditions of the grid after fine-tuning and calibration of the developed model.
2. **Design and development of the ABCM platforms:** The design and development of two Active Balancing and Congestion Management (ABCM) platforms, one for the transmission (ABCM-T) and one for the distribution grid (ABCM-D) are designed by first elucidating their functional requirements, architecture, and system use cases that will be included. Four essential tools aligned with the Cyprus demo system use cases are developed and included in the ABCM-T and ABCM-D platform namely: the real time monitoring, prequalification, FSP response evaluation and distribution grid coordination. The real time monitoring tools developed for the transmission and the distribution grid, processes real time measurements and visualize the operating condition of the grids in real time. Furthermore, the prequalification tool was developed for ensuring that the participation of FSPs located at the distribution grid will not affect the operation of the distribution grid by providing frequency support to the grid. Through the prequalification tool the limits for the all the HV/MV interfaces of the Cyprus power grid are calculated and passed to the Global market prior to the market clearing to be considered in the clearing procedure. Another important tool for the operators that was developed in the Cyprus demo is the FSP response evaluation. This tool is responsible for examining the FSPs that were chosen (their bids were cleared) to participate in congestion management services if they respond according to the cleared bids. Nevertheless, the distribution grid coordination encompasses a set of innovative services that contribute to the congestion management of the distribution

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grid. The innovative services that were developed and examined in the Cyprus demo are real and reactive upward and downward flexibility services, and the phase balancing. All these tools are integrated in the ABCM-T and ABCM-D platform that operated in the TSO and DSO control centre respectively.

3. **Development of a new ancillary service market framework:** The development of a new ancillary services market framework is a central focus of the Cyprus demo. Through this new market framework, FSPs in the distribution grid are able to provide ancillary services to the grid through their participation in the market. Three different market levels are developed and operated in the Cyprus demo, the Intra-Day Local DSO Ancillary Services Market, the Intra-Day TSO FCR Market, and the Near Real Time Local DSO Ancillary Services Market.
4. **Integration with OneNet system:** The OneNet system, which was developed as horizontal information exchange enabler for all the OneNet demos, acts as a facilitator for information exchange among various stakeholders in the Cyprus demo, including the DSO, TSO, Market operators, and FSPs in the Cyprus demo. Through the OneNet system the operators can coordinate seamlessly for the proper operation the Cyprus system, while market operators are able to procure and publish electricity market products to the market participants (FSPs). On the other hand, the FSPs can send their offers for the procured market products and services.
5. **Actual prosumer integration:** Lastly, the integration of a real residential prosumer within the demo is facilitate in the digital twin of the Cyprus system. The actual prosumer is coordinated by the DSO by the ABCM-D platform for the provision of flexibility services to the grid. The actions taken by the actual prosumers are replicated to the digital twin through the live feeding of smart meter data to the digital twin environment, demonstrating the project's tangible applicability and potential for individuals to actively participate in the energy transition.

The Cyprus demo in the OneNet project represents a pioneering effort in addressing the challenges of RES integration within the Cyprus power system. It showcases innovative solutions, advanced digital twin technology, the development of a market framework, seamless stakeholder coordination, and tangible prosumer engagement.

1 Introduction

Within the framework of the OneNet project, the Southern cluster demonstrator implements two pilot projects located in Greece and Cyprus, respectively. These countries and their respective pilot programs are currently encountering diverse challenges. The primary objective of the two pilot projects is to address the challenges of Transmission System Operators (TSOs), Distribution System Operators (DSOs), market operators, market participants and consumers in both nations, taking into account the distinct market and regulatory intricacies. Simultaneously, they introduce an inventive and collaborative approach to facilitate effective TSO-DSO coordination, enabling the provision of shared services and enhanced flexibility. The main focus of this deliverable is to describe the implementation activities conducted during the Cyprus demonstration in order to achieve the aforementioned objectives.

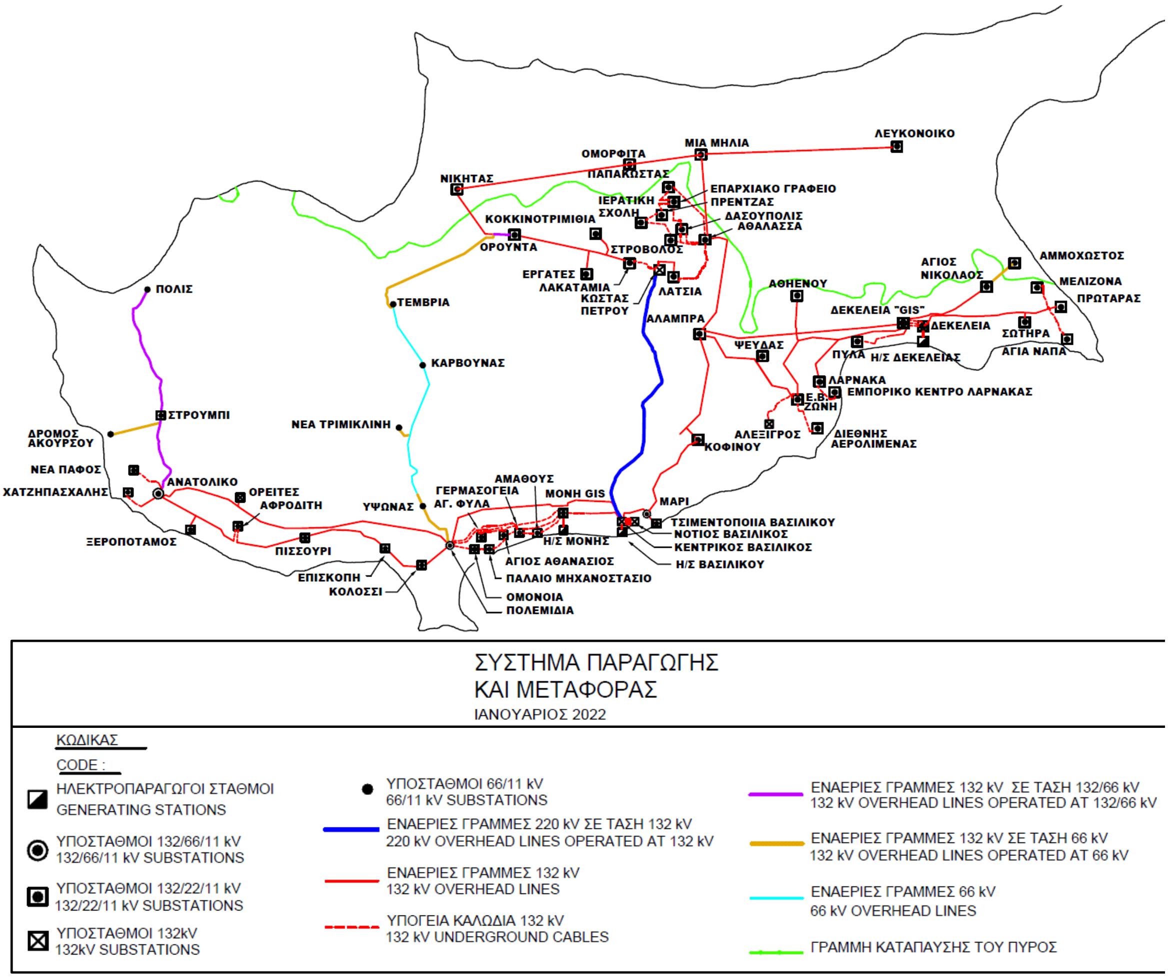

Figure 1: The electricity system of Cyprus (source: Cyprus Transmission System Operator (TSOC)).

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The Cyprus electricity system, as depicted in Figure 1, currently operates as a non-interconnected island; however, plans are in progress for an interconnection with Crete and Israel through the EuroAsia Interconnector Project, co-funded under the CEF as a PCI. This endeavour aims to link the Cypriot system to the pan-European electricity backbone network and the Israeli network, thus establishing a bridge between Europe and the Middle East. Presently, the Cypriot electricity market has undergone liberalization, allowing multiple generation and retail supply companies to partake in a competitive market, although the EAC retains substantial control with nearly 100% of retail supply and over 90% of generation. In a bid to foster market competition, Cyprus has been diligently reformulating its electricity market arrangements, with the Cyprus Transmission System Operator (TSO) introducing Trading and Settlement Rules (TSR) as comprehensive market regulations. In order to address the challenges brought forth by fluctuating renewable energy sources, energy efficiency concerns, and distributed generation, TSO and DSO efforts are pivotal to optimizing system services and leveraging flexibility resources. To confront these impending challenges, the TSO has prepared a long-term projection for the annual maximum generation (in MWh) spanning from 2021 to 2028, as illustrated in Figure 2. This forecast anticipates a substantial surge in maximum generation over the next seven years, estimating an increment of around 2000 GWh in comparison to the current capacity.

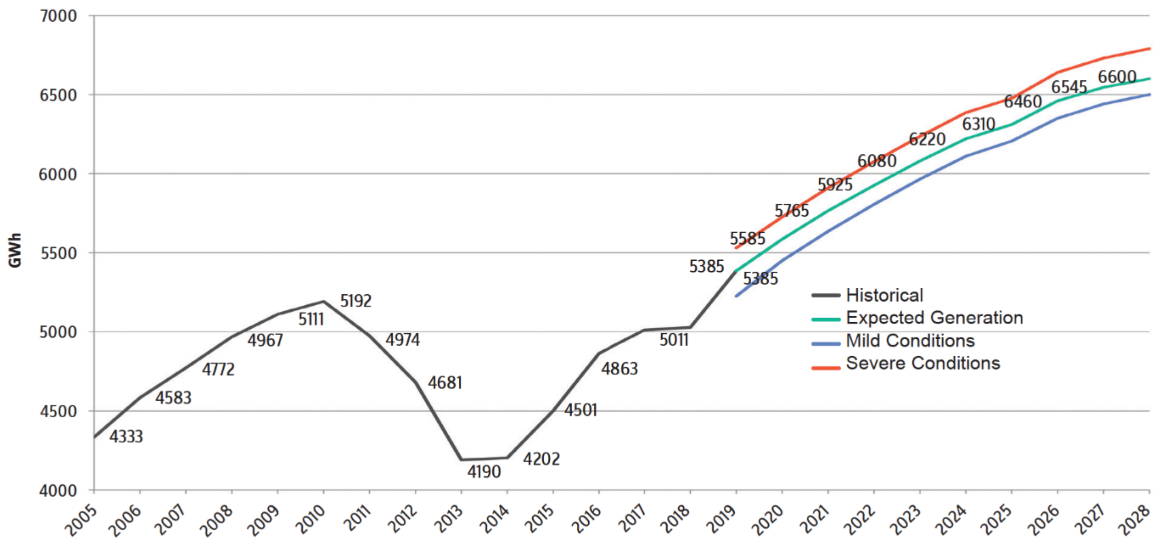

Figure 2: Long-term load forecast until 2028

Considering the isolation of Cyprus' power system and its heavy dependence on oil-powered plants for generation, a significant enhancement in the flexibility of the nation's power infrastructure is imperative to accommodate the anticipated surge in demand in the coming years. The existing installed power generation capacity of around 1740 MW, predominantly provided by the Electricity Authority of Cyprus, serves as the foundation. Aligned with the Cyprus' Integrated National Energy and Climate Plan [1], Cyprus is mandated to achieve 23% Renewable Energy Source (RES) penetration in gross energy consumption by 2030, with a specific

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target of 26% electricity production from RES (RES up to 39% for heating and cooling and up to 14% for transport), to reduce CO2 emissions by 21% compared to 2005 levels, in compliance with EU requirements. Presently, RES constitutes 17.2% of the total electricity consumption, sourced from 431.1 MW of photovoltaic systems and 157.5 MW of wind systems in 2022 [2]. A notable increase in RES contribution is anticipated, driven by favourable weather conditions. However, before integrating additional RES, strengthening the flexibility of Cyprus' small power network is crucial. The Cyprus power grid enforces caps of 650 MW for photovoltaic and 175 MW for wind installations, resulting in a feasible 21.73% RES penetration, determined collaboratively by the Transmission System Operator (TSOC), the national Distribution System Operator (DSO), and the KIOS Centre of Excellence to ensure grid stability. As such, the existing limitations in the power system's flexibility impede higher RES penetration. Addressing this, the Cyprus TSO curtails wind energy during low-demand periods to maintain generation and demand balance, despite wind's sub-5% penetration; this could be mitigated by refining forecasting methods (as the current methods that are being utilized by the TSO have a normalized error above the nominal limits). Moreover, integrating grid storage stands as a favourable approach for increasing RES penetration in Cyprus' isolated power grid. The key actions that will amplify the nation's power system flexibility encompass various factors such as:

- **The interconnection of the Cyprus system with Israel and Greece through EuroAsia Interconnector**

  This connection is anticipated to enhance the flexibility of the Cyprus power network due to the utilization of a 2 GW HVDC link that will interconnect the three systems. With this interconnection in place, it is expected that the need to curtail the RES will be minimized.

- **The operation of the electricity market following a Net-Pool Market model**

  The operation of the electricity market in 2024 is foreseen to enhance the system's flexibility through the increased involvement of additional suppliers in the Cyprus electricity market. The market model that will be used in the Cyprus electricity market aligns with the third energy package suggested by the European Commission. It is necessary to establish a regulatory framework that fosters ancillary services, storage, and effective management of demand response. These measures will certainly contribute to reinforcing market flexibility. Additionally, specific incentives ought to be introduced to motivate prosumers or aggregators to engage actively in the market.

1.1 Task 8.3-Development and implementation of the platform in Cyprus

Based on the current situation in Cyprus, Task 8.3 of the OneNet project aims to develop innovative tools for monitoring, control and management of transmission and distribution grid. These tools were integrated into the ABCM-T (transmission grid) and the ABCM-D (distribution grid) platform that were also developed in Task 8.3. Furthermore, within this task a new electricity market framework was developed that facilitates the provision of ancillary services by the FSPs located at the transmission and the distribution grid. All the tools and methodologies that were developed in Task 8.3. are tested, validated and demonstrated in the Cyprus demonstration framework that encompasses the Cyprus digital twin power system that was also developed in Task 8.3, as well different HIL setups that facilitate the integration of the developed platform with the real time digital twin power system. Within Task 8.3., all the developed tools are tested, validated and demonstrated through 'dry-run' scenarios in the operational Cyprus demonstration simulation environment. In this Task, University of Cyprus lead the efforts, while EAC, which is the grid owner and the DSO, and TSO Cyprus contributed significantly.

1.2 Objectives of the Cypriot demonstration

The abovementioned pivotal factors are not expected to be immediately implemented, but it is believed that within a 10-year horizon, the flexibility of the Cyprus power system will undergo significant enhancement. Based on the features and characteristics of the Cyprus power system, the Cyprus demo objectives are twofold:

- Firstly, the project aims to maximize the penetration of Renewable Energy Sources (RES) within the Cyprus electricity system. This objective is pursued through the development and demonstration of an effective collaboration framework that brings together the Transmission System Operator (TSO), the Distribution System Operator (DSO), and the Market.
- Secondly, the project is dedicated to enabling the provision of flexibility services within the electricity system. To achieve this, the project empowers prosumers to actively participate in the process. By encouraging their involvement, the project aims to create a dynamic and responsive energy system that can effectively accommodate fluctuations in energy demand and supply, ultimately enhancing the system's overall flexibility.

1.3 Outline of the Deliverable

This deliverable encompasses various sections related to the Cyprus demo under the OneNet project. Section 2 includes the overall description of the Cyprus demo and delves into its business and system use cases, particularly focusing on active power flexibility, reactive power flexibility and power quality. Additionally, this section explores specific scenarios of the Cyprus demo, covering frequency balancing and congestion management. Section 3 discusses the development of the Cyprus power system Digital Twin. Section 4 focuses on the implementation phases, outlining the key stages involved in the project, including the development of the Cyprus power system digital twin, the ABCM platform design and development, the design and development of a new ancillary service market framework, the Cyprus demo integration through the OneNet system, and the validation and evaluation framework. Furthermore, Section 4 delves into the detailed design of the ABCM

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platform, presenting a general description, the functional requirements for the ABCM platforms (ABCM-T and ABCM-D), and their architecture. The implementation specifics within this section include real-time monitoring, pre-qualification, evaluation of the FSP (Flexibility Service Provider) response, and coordination of the distribution grid. Section 5 focuses on the design and development of the new ancillary services market. Section 6 addresses the Cyprus Demo Integration through the OneNet System, with a particular emphasis on Information Exchange and OneNet System Integration. Section 7 describes the integration of an actual prosumer to the Cyprus demo and the deliverable concludes with Section 7.

1.4 How to Read this Document

For better understanding of this deliverable, it is important for the reader to read Deliverable 8.1 [3] that describes the requirements and specification of the pilots in Greece and Cyprus that forms the Southern cluster demo. Furthermore, the reader can find more details regarding BUCs and SUCs of the Cyprus demo in Deliverable 5.1 [4] and in Deliverable 2.3 [5] respectively, while details about the developed electricity market framework can be also found Deliverable 3.4 [6]. Finally, the reader can find the KPIs of the Cyprus demo along with their detailed descriptions and formulas in Deliverable 2.4 [7].

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2 Cyprus Demo Description

2.1 Overall description

The main objective of the Cyprus demo is to demonstrate an efficient collaboration among various stakeholders in the Cyprus power system, including the TSO, DSO, Market Operator, and prosumer/aggregator. This collaboration will be facilitated through the exchange of vital information using the OneNet system, alongside the development of innovative control and monitoring tools within Task 8.3. It should be noted that the OneNet system creates a fully scalable architecture that enables the whole European electrical system to operate as a single efficient platform in which a variety of markets allow the universal participation of stakeholders regardless of their physical location, at every level from small consumer to large producers [8]. The OneNet system in the Cyprus demo enable the seamless information exchange between the different actors in the Cyprus system (i.e., TSO, DSO, market operator, FSPs).

The specific aims of the demo encompass enabling prosumers to offer active power, reactive power, and power quality flexibility services to the power grid, while also achieving a higher penetration of Renewable Energy Sources (RES) without compromising system stability and integrity. Additionally, the demo seeks to highlight the substantial benefits achievable through effective coordination of critical power system actors via the OneNet System.

The Cyprus power system's current situation presents challenges due to its islanded nature, making it susceptible to potential disruptions arising from increased variable renewable source penetration. Moreover, the concentration of Photovoltaic (PV) installations in specific distribution grid areas results in local congestion problems caused by high volumes of reverse power flow. Furthermore, the absence of flexibility resources beyond conventional generation plants exacerbates these issues.

The Cyprus demo aims to address these challenges by showcasing the effective collaboration among the Cyprus TSO, Cyprus DSO, and the future Market Operator. Under the coordination of the University of Cyprus, the demo activities will involve active participation from the Cyprus TSO and Cyprus DSO, providing crucial measurements, topology data, and historical information related to the transmission and distribution grids.

The overall architecture of the Cyprus demo, as depicted in Figure 3, illustrates all key stakeholders and integrated platforms. The two pivotal platforms, ABCM-D and ABCM-T, focus on Active Balancing and Congestion Management for the DSO and TSO, respectively. Developed within Task 8.3 of the OneNet project, these platforms play a critical role in coordinating the Cyprus TSO, DSO, Market, and flexibility service providers (FSPs) like aggregators, prosumers, and large generation plants. The ABCM-T platform offers real-time monitoring of the transmission level using PMU measurements, pre-qualifies products and services procured by

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large FSPs to ensure proper operation, and evaluates FSPs' responses during disturbances. Similarly, the ABCM-D platform enables real-time monitoring of the distribution grid through SCADA and smart meter measurements, pre-qualifies products and services procured by FSPs at the distribution level, coordinates flexibility services in the distribution grid, and conducts online evaluations of FSPs' responses for frequency balancing and congestion management. Detailed functional requirements for these platforms are available in Section 4.2.

The seamless exchange of information in the Cyprus demo is facilitated by the OneNet system, playing a crucial coordination role among the different actors. Information exchange flows between the OneNet system and the main stakeholders are elaborated in Section 6. In the absence of an operational market in Cyprus, the demo incorporates a fictitious market that includes both the TSO market and a DSO local market. These markets are developed based on pre-existing setups without introducing new market designs.

The entire demonstration setup will occur in a controlled hardware-in-the-loop (HIL) environment, utilizing the digital twin of the Cyprus transmission and distribution systems. The real-time simulator will create these digital twin systems using information from both the Cyprus TSO and DSO. The controlled HIL environment provides the opportunity to test various scenarios under the two Business Use Cases of the demo, focusing on active power flexibility and Reactive power flexibility and power quality.

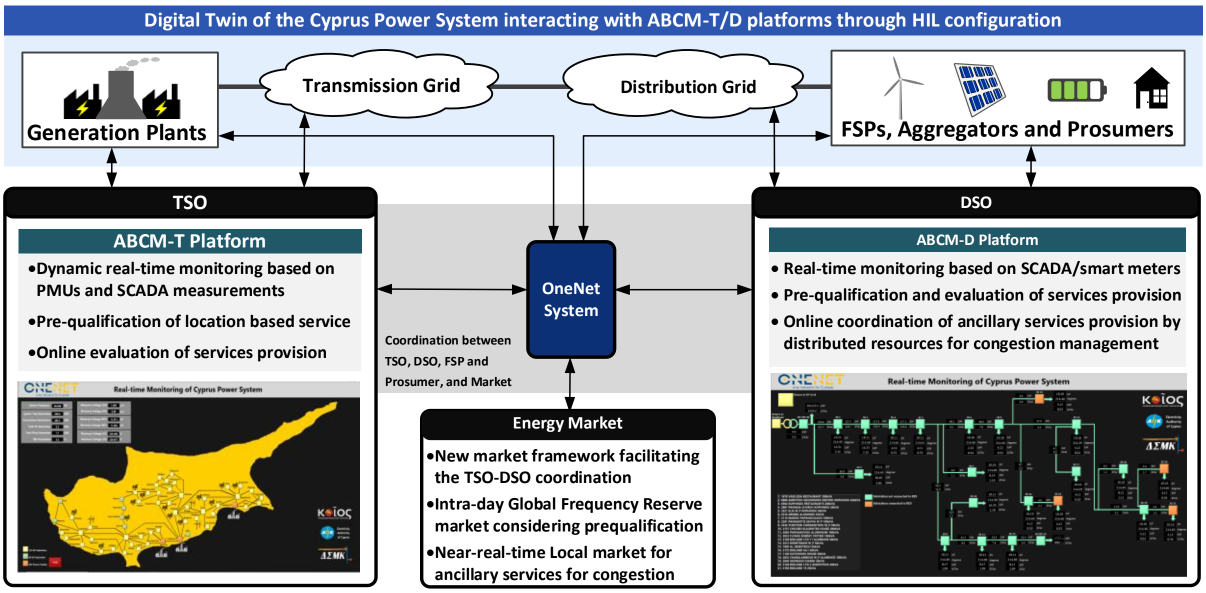

Figure 3: Cyprus demo general architecture

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2.2 Business and system use cases of the Cyprus demo

The ABCM platforms for the TSO and DSO demonstrate a seamless coordination between the TSO, the DSO and the flexible services providers to increase system flexibilities and improve the operating conditions, the stability and the power quality of the Cyprus power system. The main business use cases (BUCs) for this demonstration among with the corresponding system use case (SUCs) and products will be analysed in this section. Furthermore, the assumptions and prerequisites for this demonstration are stated and the related key performance indicators (KPIs) that will be used in the evaluation framework are presented.

2.2.1 Business Use Cases

Two main BUCs have been identified for the ABCM platforms and the Cyprus demonstration. The first BUC focuses on enhancing the active power flexibility of the power system while the second BUC targets on reactive power and power quality flexibilities. Each BUC is described below while further information can be found in Deliverable 2.3: Business Use Cases for the OneNet [5].

Business Use Case 1: Active power flexibility

Business Use Case 1 focuses on active power flexibility in Cyprus' power system, favouring high PV penetration. The high-RES penetration, combined with an islanded system, challenges frequency stability and balancing due to unpredictable RES. Concentrated PVs in certain distribution feeders cause local congestion, leading to voltage and thermal violations. The primary objective of the BUC is enhancing active power flexibility by providing coordinated ancillary services like peak shaving and energy shifting through the distributed resources such as energy storage and PV systems. The main goals include improving frequency stability and relieving congestion.

Business Use Case 2: Reactive power flexibility and power quality

This use case focuses on reactive power flexibility and power quality in Cyprus' power system. However, high PV penetration in specific feeders causes local congestion, leading to voltage and thermal violations. Most loads being single-phase connected exacerbate phase imbalances, affecting power quality and grid capacity. This BUC aims to enhance reactive power flexibility and power quality by coordinating the ancillary services provision. It includes congestion management and phase balancing, provided by distributed flexible resources within distribution grids. The main objectives are to reduce energy losses and improve grid efficiency, relieve congestion, maintain capacity limits, and improve power quality while symmetrizing phase loading conditions at the distribution level.

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2.2.2 System Use Cases

The following system use cases (SUCs) have been identified for the Cyprus demo and will be included in the ABCM-T and ABCM-D platforms. These four SUCs will be used for accomplishing both BUCs for the Cyprus demo. The SUCs consider the monitoring of the operating conditions at both the transmission and the distribution grid, the prequalification of the location-based limits for the market products, the evaluation of the FSPs response, and the online coordination of the flexibility services by the distributed resources [4]. Brief descriptions of the SUCs are listed below while details about their implementation are provided in Section 4.4:

- **SUC1 – Real-time monitoring of the grid:** The operating condition of the transmission and distribution grids will be monitored using real-time measurements. In the case of the transmission grid, PMU and SCADA measurements will be used in a real-time monitoring scheme, while in the case of the distribution grid smart meter and SCADA measurements will be used.
- **SUC2 – Prequalification of the location-based limit of each market product:** Use available monitoring information (from SCADA, PMUs, smart meters) and historical data to determine the location-based limits. In the case of the transmission grid the location-based limit will be determined at the primary substation (HV/MV interface), while in the distribution grid the limit will be calculated at the secondary substation (MV/LV interface). The prequalification of the limits will be done for a specific time interval ahead according to the market time frame.
- **SUC3 – Evaluation of the FSPs response:** Use available monitoring information (from SCADA, smart meters, PMUs) for evaluating the response of the FSPs located at the transmission and the distribution grids after the provision of grid services. This SUC will determine if the FSPs response corresponds to the awarded bids cleared by the TSO and the local DSO market.
- **SUC4 – Coordination of distributed flexible resources:** Use available monitoring information (from SCADA, smart meters) in order to automatically coordinate the operation of the distributed flexible resources to ensure the proper, efficient, and high power quality of the distribution grid.

It should be noted that SUCs 1-3 were included in both the ABCM-T and ABCM-D platforms and each of these SUCs were tailored according to the specific characteristics of the transmission and distribution grids respectively. SUC 4 was developed for the case of the distribution grid and was only included in the ABCM-D platform.

2.3 Scenarios of the Cyprus Demo

During the Cyprus demo, two primary scenarios were examined for demonstration purposes, closely related to the business use case explored in Section 2.2. The first scenario addressed the engagement of FSPs to restore system frequency after a disturbance, while the second scenario focused on managing congestion in the

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distribution grid, encompassing sub-scenarios for addressing line overloading and power quality issues. Detailed descriptions of these scenarios are provided in the subsequent sections. It should be noted, that through these scenarios the different KPIs for the Cyprus demo were evaluated and will be included in D8.4, while they have been provided to Task 11.1, in which the evaluation of all the OneNet demonstrations will be done.

2.3.1 Frequency balancing

The frequency balancing scenario for the grid addresses the challenge of generation loss after a grid fault. This loss disrupts the equilibrium between generation and demand, resulting in a significant frequency disturbance that can impact the frequency stability of the system. To counter this, flexible resources such as Flexibility Service Providers (FSPs) and prosumers, who have been awarded participation in the frequency balancing through the TSO market, are automatically activated to provide automatic frequency support and synthetic inertia to restore the frequency balance. It is important to highlight that the bids of the FSPs located at the distribution grid and participating in this scenario were forwarded by the Intra-Day DSO market. Furthermore, prequalification limits (calculated through the prequalification scheme) for the transformer connected between the HV/MV interfaces are also sent to the TSO market. Similarly, FSPs operating at the transmission level and participating in the TSO market must meet the prequalification criteria imposed by the TSO for their awarded activation products. Subsequent to the provision of services by the participating FSPs, the TSO and the DSO conduct online evaluations of the FSPs' response to ensure their proper operation, and an evaluation report is then communicated to the energy market.

2.3.2 Congestion management

The congestion management scenario within the distribution grid addresses issues like line overloading and power quality by activating flexibility services from local distributed resources. This involves authorized FSPs in the distribution feeder. In contrast to frequency balancing, flexibility resources are engaged through the ABCM-D platform when a feeder congestion occurs. The DSO submits offers to the local DSO market and the FSPs submit availability bids. After clearing the local DSO market for procured products, approved bids are shared with the FSPs. During congestion, when the ABCM-D platform detects violations through real-time monitoring, coordination signals are sent to the market-approved FSPs to mitigate the congestion. The ABCM-D platform evaluates FSPs' responses, and the DSO sends an assessment report to the DSO local market.

2.4 Implementation phases

The Cyprus demo includes 4 main implementation phases that are executed in order to develop a demonstration environment where the two main scenarios described above were implemented. These phases

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are described briefly below while a detailed discussion for each phase is provided in the next Sections of the deliverable.

- **Phase 1 - Development of the Cyprus power system digital twin**

  The digital twin of the Cyprus Power System grid has been developed in MATLAB/Simulink [9] using real data provided by EAC and TSO of Cyprus and it has been simulated and tested in real time using the OPAL Real-Time Simulator [10]. It consists of the transmission system, including the two main power stations with synchronous generators located at Vasilikos and Dhekelia areas, high voltage power lines and substations. Furthermore, a part of the Cyprus distribution grid, which encompasses the medium and low voltage grids, was implemented. It should be noted that, Photovoltaic/Battery Energy Storage Systems (PV/BESS), have been implemented at all three voltage level systems. Real time data derived from the Cyprus power system digital twin, are sent in real time, and stored in a dedicated database to be used by the SUCs. Furthermore, for visualization purposes a monitoring interface has been also developed to facilitate the system monitoring using the LabVIEW real-time software [11]. More details regarding the implementation of the Cyprus power system digital twin can be found in Section 3, while for the monitoring scheme developed in OneNet Cyprus demo can be found in Section 4.4.1.

- **Phase 2 - ABCM platforms design and development**

  In this phase the architecture and the functional requirements of the two ABCM platforms were designed and defined respectively. Furthermore, the tools regarding the SUCs were developed and integrated in the two platforms to enable efficient and effective operation on both transmission and distribution levels. MATLAB, along with its App Designer [12] application for HMI designing, is utilized to develop the two platforms' operational features. These features facilitate the management of the Cyprus power system digital twin, aggregate and store actual or virtual measurements from PMUs and smart meters, establish communication between TSO/DSO, FSPs, and the market, send control signals to FSPs, conduct post-analysis of the grid operation, find pre-qualification limits, and evaluate FSPs' responses. More details regarding the design and development of the ABCM platforms can be found in Section 4.

- **Phase 3 - Design and development of a new ancillary service market framework**

  The Cyprus demo architecture was designed from scratch since no operational market exists in Cyprus yet. This phase included the design and development of the ancillary service market. The interfaces for each market participant and the market clearing optimization algorithms are developed using MATLAB App Designer. Each category of market participant has a respective Human Machine Interface (HMI) designed. The HMIs enable the FSPs/operators to bid new offers/demand and receive market clearing results. More details regarding the new ancillary service market framework designed in OneNet Cyprus demo can be found in Section 5.

- **Phase 4 - Cyprus demo integration through the OneNet system**

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The OneNet system is utilized as the communication channel and database for market participants in the Cyprus Demo. Through this system, market participants establish communication to exchange information about needs, offers and market clearing results for the provided services. In the Cyprus demo, the OneNet system acts as the communication exchange facilitator between the TSO (through ABCM-T platform), the DSO (through ABCM-D platform), the market operators, and the FSPs connected either at the transmission or the distribution grid. It is clarified that OneNet system is used for exchanging the market related data (e.g., generation offers, demand bids, pre-qualification limits, market clearing results), while for operation purposes direct communication between the operators and the FSPs is considered to facilitate the real-time coordination of the grid operation. More details about the OneNet system integration to the Cyprus demo are provided in Section 6.

2.5 Validation and evaluation framework

The validation and testing environment utilized to showcase the diverse objectives of the Cyprus demonstration is depicted in Figure 4 . All scenarios were executed through dry run simulations, dividing the Cyprus demonstration into the Digital Twin and Hardware-in-the-Loop (HIL) demonstration environment and the Information and Communication (ICT) environment. Within the digital twin and HIL environment, the real-time simulator (OPAL-RT OP5707) played a pivotal role, enabling the development and testing of digital twins for the Cyprus transmission and distribution systems, emulating real-world conditions. To facilitate real-time monitoring, distinct metering equipment was employed at the transmission and distribution levels. The transmission system incorporated 18 PMUs, emulated in the real-time simulator. Similarly, the distribution system's monitoring employed smart meters or SCADA measurements, emulated in the real-time simulator as well. These strategies were mirrored across both levels, with measurements transferred from the real-time simulator to the ABCM-T and ABCM-D platforms for enhanced monitoring. Flexible Service Providers (FSPs) were also simulated in the real-time simulator and locally controlled through innovative techniques developed in Task 8.3 to enable advanced functionalities (e.g., droop control and virtual inertia, active and reactive power flexibilities, phase balancing functionalities, etc.). Moreover, the two ABCM platforms receive measurements from different measuring equipment (e.g., PMUs, smart meters), which is utilized to facilitate various functionalities inherent to each platform. At the same time, fast communication between the TSO (ABCM-T platform) and the DSO (ABCM-D platform) and the FSPs (emulated in the digital twin) is established, as indicated with red arrow in Figure 4, to enable the real-time coordination of the power system for congestion management purposes.

The ICT environment is responsible for overseeing the communication and exchange of information among the various entities and systems within the Cyprus demonstration. Specifically, this ICT environment comprises the ABCM-T and ABCM-D platforms, situated respectively within the control centres of the TSO and the DSO. It

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also encompasses the energy market (for both TSO and DSO) and the OneNet system. The transfer of all the market related information among all participants within the Cyprus demonstration – namely the TSO, DSO, Market, and Flexible Service Providers (FSPs) – is managed through the utilization of the OneNet system, as demonstrated with blue arrows in Figure 4.

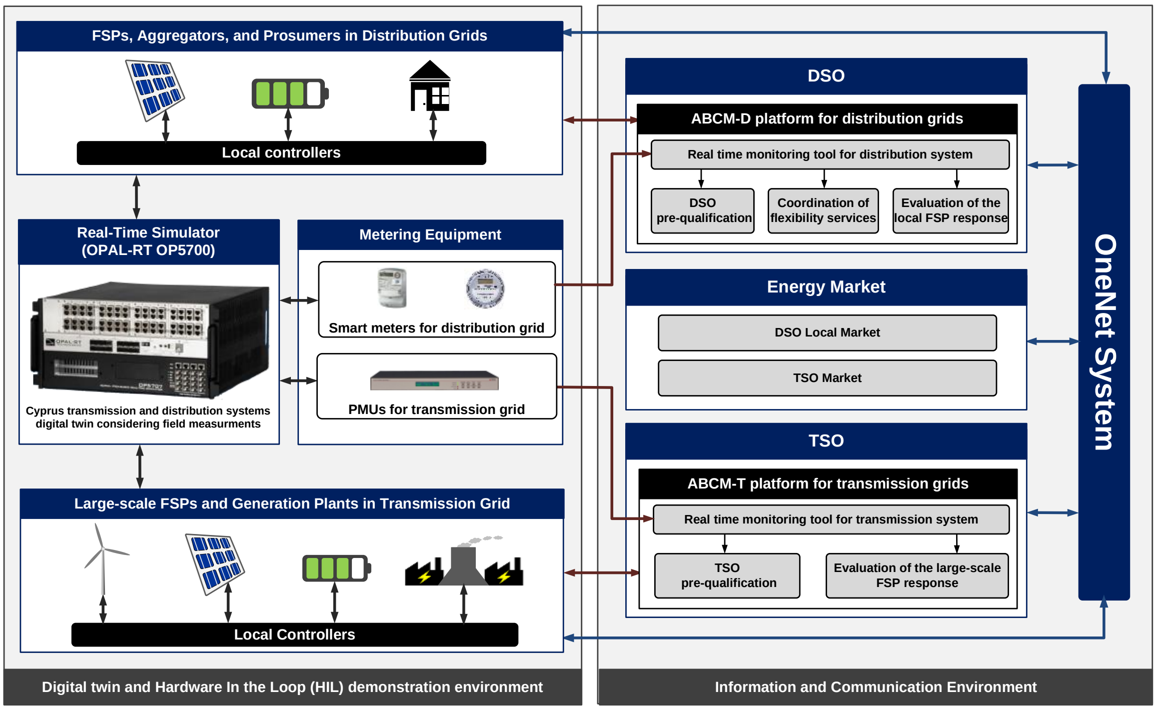

Figure 4: Testing and validation framework of the Cyprus demo (blue arrows represent data exchange for market operation purposes, while red arrows denote fast data exchange signals for real-time operation

The scenarios described in Section 2.3 were used for the testing, validation and demonstration of the Cyprus demo concept employing the framework depicted in Figure 4. Further, the overall evaluation framework for the Cyprus demo encompasses a comprehensive set of Key Performance Indicators (KPIs) to assess the effectiveness and success of the demonstration. These KPIs include: KPI1 - Rate of Change of Frequency improvement, which measures the progress in enhancing the frequency stability of the system; KPI2 - Improvement of Frequency Nadir, to evaluate the extent of improvement in the lowest frequency experienced during disturbances; KPI3 - Overloading, to monitor and address instances of line overloading in the distribution grid; KPI4 - Improvement on voltage limits violations, indicating the effectiveness of measures taken to prevent voltage limit breaches; KPI5 - Reduction of Energy Losses, which measures the reduction in energy losses achieved through improved system management; KPI6 - Reduction of Loading Asymmetries, to assess the level of balance achieved in loading distribution; KPI7 - Power Factor (PF) Improvement, indicating improvements in power factor performance; KPI8 - Number of Distributed Energy Resources (DER) available for Balancing Service Providers (BSPs), reflecting the availability of DERs for balancing services; and KPI9 - Volume of Balancing Service Offers for Up Reserves, which

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quantifies the volume of offers received for up reserves to ensure adequate system balancing. More information regarding the KPIs of the Cyprus demo are provided in Deliverable 8.1 [3], while the formulas for the calculation of the KPIs are provided in Deliverable 2.4 [7]. These KPIs will be included in D8.4 and will provide valuable insights into the overall performance and impact of the Cyprus demo, enabling a thorough evaluation of its contributions towards enhancing the grid flexibility and efficiency.

3 Development of the Cyprus Power System Digital Twin

A key activity of the OneNet project is the development of a digital twin for the Cyprus power system. This is geared towards the development, integration, and showcase of innovative solutions for the Cyprus demo in a realistic and relevant environment, achieving a Technology Readiness Level (TRL) of 6. The Cyprus demo focuses on the operational aspects of the power system and explores novel solutions to alleviate congestion issues, such as overloading, and to enhance system's stability under intense disturbances, like the loss of a generator. To assess the efficacy of these solutions, it's essential to trigger abnormal conditions that could potentially damage the power infrastructure. To avoid this risk, the digital twin of the Cyprus power system becomes crucial. This twin mirrors the real-time operation of the actual system in a virtual domain with high accuracy. As a result, it establishes a non-invasive environment where extreme and abnormal scenarios can be tested without compromising system integrity. Hence, this non-invasive digital twin setup is vital for validating and demonstrating the OneNet Cyprus demo solutions for enhancing the operation capabilities of the power system through the seamless and effective coordination between all stakeholders.

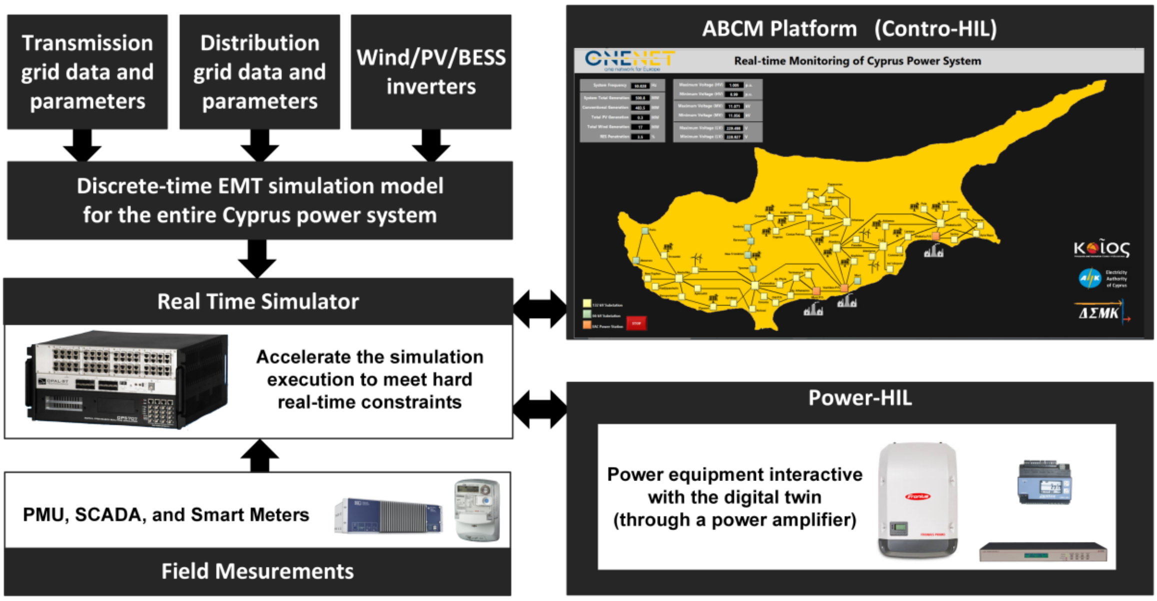

Figure 5: Testing and validation framework of the Cyprus demo

For the development of such a country-level power system digital twin, the main steps are described below and are presented in a visualized manner in Figure 5.

- **Step 1 - Development of an accurate simulation model for the Cyprus power system**

  Collection of data: The first step towards the development of the digital twin is related to the development of a simulation model that can accurately replicate the operating conditions of the power system. To achieve this, design details, parameters and profiles are needed for all the components of

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the system. TSOC who is the Cyprus TSO has collected and shared with the UCY all the required information for modelling overhead lines, cables, transformers, substation protection schemes, loading conditions, etc., which are related to the transmission grid. Similarly, EAC, who is the DSO and the grid owner of Cyprus, has collected and shared the corresponding information regarding the selected parts of the distribution grid. Furthermore, information and design details about the two conventional power stations available in Cyprus, and the PV and Wind power capacity installed per substation have been collected as well.

Transmission and distribution grid characteristics: In more technical details, the transmission system includes 58 substations which have been modelled using full details. The two conventional power stations connected at Vasilikos and Dhekelia areas, consisting of three synchronous machines at a rated power of 172.5 MW each, and six 75 MW rated power synchronous machines with excitation and governor control features (along with an AGC secondary controller), at each substation respectively.

Regarding the distribution grid, only a selected part of the distribution level has been modelled (due to complexity issues – since the real-time constrains should be ensured for the digital twin) focusing on the distribution grid in the area of Kophinou, where there is an intense penetration of PVs. The consideration of only a part of the distribution grid in the digital twin is sufficient to allow the proof-of-concept demonstration of an effective coordination between DSO, FSPs/prosumers and the market to ensure the appropriate operation of the grid. The same coordination process can be repeated in the rest distribution grid without any changes and thus, the demonstration focuses on investigating the operation of the particular part of the distribution grid while considering multiple loading/generation scenarios. The selected part of the distribution grid simulation model includes a MV distribution grid with 21 substations connected in a MV feeder and additionally, a LV distribution grid with 7 consumers/prosumers at a LV feeder, allowing access to all the voltage levels. At the rest substations, aggregated loads have been modelled using load profiles, and distributed generation has been incorporated using generation profiles injected through an aggregated inverter for the grid interconnection. In total, 224 MVA PV and BESS inverters and 156 wind power systems have been installed at the transmission system, 8 MVA PV and BESS inverters at the MV distribution system, and 30 kVA PV and BESS at the LV distribution system.

Development of advanced inverters for FSP to provision ancillary services: Since a number of PV, Wind and BESS are utilized as FSPs in this demonstration, the grid integration of these systems is enabled through typical PV/Wind/BESS inverters, designed in different power rating scales. A multi-functional control approach has been developed for these inverters ensuring the following functional capabilities: provisioning of a fast frequency response (FFR) [13], emulating virtual inertia [13], providing phase balancing services through asymmetrical current injection [14], enabling fault ride through support

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during low-voltage grid faults [15], receiving external coordination set-points to regulate the active and reactive power injection. Through, such functional capabilities, the Wind/PV/BESS inverters can be utilized as FSPs providing ancillary services to the TSO and the DSO. These advanced FSP's inverter features are particularly important for the Cyprus demo of OneNet, since one of the scenarios of the demo focuses on the provision of FFR by the FSP's inverters to support the frequency stability of the power system, while another scenario is related to the provision of phase balancing services and the external coordination of active and reactive power to relieve congestion in the distribution grid. Hence, the development and integration of advanced FSP inverters in the digital twin enables the investigation of novel scenarios where DERs are actively participating in the management and coordination of modern power systems.

Simulation model development: The entire simulation model of Cyprus power system has been developed as an Electro-Magnetic Transient (EMT) simulation model using MATLAB/Simulink and considering a discrete-time solver with a fixed solver step. The selection of the specific software and solver is related to be executed after slight modifications in a Real Time Simulator (in Step 3) to ensure the real-time constraints required for such a digital twin environment. It has been pre-validated that the simulation model can achieve stable operating conditions and its performance under some extreme conditions has been tested.

- **Step 2 – Incorporation of field measurements**

  Field data integration: After the development of the simulation model, the incorporation of field measurements is needed to replicate the operating conditions of the actual power system in the digital twin. For this purpose, 18 PMUs were installed (by UCY, EAC and TSOC through a previous project) in the transmission grid, and thus, high-resolution synchronized measurements (with 20 ms time resolution) have been received for selected days. These measurements have been processed through a state estimation algorithm [16] to identify the states and the power injection at all the busses of the transmission grid with a 20 ms time step. As a result, the time-series profiles needed for replicating the operating condition at the transmission substation have been extracted. Furthermore, SCADA measurements (provided by the TSOC and EAC) have been utilized to characterise the operation of Wind and PV systems and for time profiling the operation of the distribution grid substations. In addition, smart metering data have been utilized as well to profiling the operation of consumers/prosumers of the distribution grid.

  Model calibration: In several cases, the field measurements have been used to calibrate the parameters and models of the simulation to increase the accuracy of the digital twin. In example, erroneous transmission line parameters have been identified and the accurate parameters have been re-calculated through the use of PMU measurements [17]. This way the accuracy of the simulation model has been increased.

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Model validation: Then, a cross validation of the accuracy of the Cyprus power system simulation model has been evaluated using simulation results and field data for both steady state and dynamic performance. The validation process indicates that the developed simulation model is able to replicate the operation of the actual system with an average accuracy of 97%.

- **Step 3 – Real-time execution of the simulation model in a dedicated Real Time Simulator (RTS)**

  Real-time execution: An important feature of a digital twin is the capability for real-time execution. However, the extreme complexity of a country-level power system simulation model using EMT modelling and a small solver time step (e.g., 100 μs) does not allow a real-time time execution in a typical computer. Therefore, to meet the real-time execution requirements for the digital twin, an acceleration of the execution time of the simulation is needed by a factor of 100 to 1000 times. For this reason, a dedicated RTS is utilized to ensure real-time execution. In the case of the Cyprus demo, an OPAL-RT (OP 5707 RTS) has been used and 6 activated cores are needed to achieve real time execution. To execute the simulation model (developed in Step 1) in the RTS, appropriate modifications have been applied in the Cyprus power system Simulink model in order to make the model compatible with the RTS. These modifications include the separation of the models into different subsystems (each one to be executed in a different core), the replacement of specific blocks with the dedicated ones from the ARTEMiS Electrical Toolbox to accelerate their performance, and the configuration of the communication signals to be exchanged between the subsystems/cores to avoid communication delays. The modified model has been successfully built and loaded into the RTS hardware and a real-time execution is achieved with a 100 μs solver step. Therefore, through the RTS, the development of the real-time digital twin of the Cyprus power system is achieved.

  Control- and Power- Hardware In the Loop (Control-HIL and Power HIL): As soon as the simulation model of the Cyprus power system is running in real-time using the dedicated RTS, different control-HIL and power-HIL configurations can be developed. In particular, for the control-HIL, the communication interfaces of the RTS are used to enable the exchange of real-time data between the digital twin and the ABCM software platform in order to enable the monitoring, management and coordination of the digital twin by the tools integrated within the ABCM platform. For the data exchange between the digital twin and the software platform, typical industrial protocols have been used, such as: Modbus TCP, TCP/IP, IEEE C37.118, etc. On the other hand, for developing a power-HIL configuration, the analogue input/output interfaces of the RTS are utilized to drive power equipment (e.g., inverters, BESSs, PMUs, smart meters) through a power amplifier, while the operation of the power equipment is considered in the next solution step (next 100 μs) of the digital twin. As a result, this environment allows interactive integration of software controllers and power equipment with the digital twin.

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It should be noted that the Cyprus power system has been successfully developed and tested in WP8 of the OneNet project. The digital twin can be considered as the cornerstone of the Cyprus demo and the new solutions developed for this demo can be validated and demonstrated in a realistic and non-invasive environment. In this context, extreme conditions can be emulated within the digital twin, without risking the integrity of the Cyprus power infrastructure, and the effectiveness of the developed solutions can be demonstrated in a precise virtual environment.

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4 ABCM platform design and development

4.1 General description

The Cyprus demo fosters effective collaboration between the TSO, the DSO, and the market operator, promoting the integration of small/medium-scale flexible resources (e.g., photovoltaic, energy storage) to enhance system flexibility. This concept is achieved through efficient information exchange among various entities (TSO, DSO, TSO Market, DSO local Market, large-scale generation plants, small/medium-scale flexible service providers, aggregators, and prosumers) via the OneNet system. The demo primarily focuses on the operational level of both transmission and distribution grids, emphasizing the significance of a dedicated Active Balancing and Congestion Management (ABCM) platform to elevate the operational capabilities of the TSO and DSO. To accommodate the distinct characteristics, specifications and requirements of each system (transmission and distribution), the ABCM platform is divided into two individual platforms, ABCM-T for the Transmission grid and ABCM-D for the Distribution grid. In the subsequent sub-sections, the main functional requirements and platform architecture for each platform are detailed.

4.2 Functional requirements of the ABCM platforms

4.2.1 ABCM-T platform functional requirements

The ABCM-T platform, developed within the OneNet project, facilitates effective operational capabilities for the TSO, enabling seamless coordination between the transmission and the distribution grid through the energy market, as demonstrated in the Cyprus demo. The platform ensures the following functionalities:

- It receives real-time measurements (every 20 ms) from actual and virtual Phasor Measurement Units (PMUs) and stores them in a time-series database.
- It receives conventional measurements (SCADA measurements) from the power system's digital twin at intervals of seconds (i.e., every 5 s) and stores them in a time-series database as well.
- It sends coordination signals to flexible actuators in the digital twin to control their operation according to TSO decisions.
- It facilitates online monitoring of the transmission grid using real-time measurements from both PMUs and conventional SCADA meters to enhance the TSO's situational awareness.
- It provides post-analysis functionalities for events, allowing users to select specific time windows to receive high-resolution historical data for enhancing the situational awareness.

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- It pre-qualifies the maximum capacity of flexibility to be provided by FSPs connected at each primary substation level (HV/MV interfaces) for a specific time window ahead (i.e., 3 hours ahead) using real-time monitoring and historical measurements to define maximum location-based limits for specific services.
- It evaluates the response of large-scale FSPs located in the transmission grid and validates if their response corresponds to the awarded bids cleared by the ancillary services market, considering the operation grid conditions that automatically triggers the service provision.
- It is equipped with a human-machine interface (HMI) for real-time observation of the transmission grid's operation and post-event analysis.
- It allows the operator to validate location-based pre-qualification limits and the evaluation report for the response of FSPs before publishing them to the market operator and participants.
- It facilitates the required communication between the TSO and other entities (e.g., TSO market, FSPs participating in the TSO market) in a standardized manner through the OneNet system. The ABCM-T platform is compatible with the OneNet system to facilitate communication and data exchange between different entities.

4.2.2 ABCM-D platform functional characteristics

The ABCM-D platform is tailored to meet the specific needs of the DSOs, allowing them to monitor the system's operation, procure products into the market, define location-based limits, evaluate the response of local FSPs, and coordinate flexibility services in real-time. The ABCM-D platform ensures the following functional requirements:

- It receives periodic measurements (e.g., every 30 seconds, every 15 minutes) from actual or virtual smart meters (emulated within the digital twin) and stores them in a time-series database.
- It receives conventional measurements (SCADA measurements) from the digital twin of the distribution grid every 5 seconds and stores them in a database.
- It sends coordination signals to virtual flexible actuators located within the digital twin or to actual flexible actors to control their operation according to the DSO decisions. The actual flexible actors (e.g., a battery storage system, a residential prosumer) can be connected to the grid or to a power amplifier and integrated with the Cyprus distribution grid digital twin through a software or hardware in the loop configuration.
- It facilitates online monitoring of the distribution grid, considering real-time measurements from both smart meters at the end-users and conventional SCADA meters to enhance the DSO's situational awareness.

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- It uses real-time monitoring and historical measurements to pre-qualify the available capacity of the distribution grid at each secondary substation level (MV/LV interfaces) for a specific time window ahead (i.e., 3 hours ahead), defining maximum location-based limits for specific local services.
- It evaluates the response of small/medium-scale FSPs located at the distribution grid and validates if their response corresponds to the awarded bids cleared by the local market, while considering the coordination signals sent by the DSO to activate specific ancillary services.
- It automatically coordinates the operation of flexibility services to ensure adequate and high-quality operation of the distribution grid. In this context, the DSO should be able to send coordination signals to flexible FSPs to change their active (*P*) and reactive (*Q*) power injection accordingly, in order to relieve congestion at the local distribution level. In addition, when three-phase FSPs are capable of individually controlling the power injection at each phase (on purpose asymmetric power injection capabilities), then the DSO should be able to coordinate those FSPs to symmetrize the loading conditions in the grid in an effort to relieve the congestion of the most loaded phase and to increase the power quality of the distribution grid.
- It is equipped with an HMI to allow the DSO to observe the distribution grid's operation and coordinate the system's operation.
- Through the HMI, the operator can validate location-based pre-qualification limits and the evaluation report for the response of the FSPs before publishing them to the local market operator and the participants in the DSO local market.
- The ABCM-D platform facilitates the required communication between the DSO and other entities (i.e., DSO local market, FSPs participating in the DSO market) in a standardized manner through the OneNet system. Thus, the ABCM-D platform is compatible with the OneNet system to facilitate communication and data exchange between different entities.

4.3 ABCM platform architecture

As mentioned earlier, the ABCM platform comprises two distinct components: ABCM-T and ABCM-D, serving the needs of the TSO and DSOs respectively. The ABCM-T platform is particularly designed to align with the distinct characteristics and requirements of TSOs, while the ABCM-D platform is specifically tailored to address the unique needs and requirements of DSOs. Consequently, each platform features its own exclusive architecture, which is elaborated upon in the following sub-sections.

4.3.1 ABCM-T platform architecture

The architecture of the ABCM-T platform is illustrated in Figure 6, specifically designed for the efficient management of the transmission grid within the OneNet Cyprus demo. This platform needs to operate in real-

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time and interface seamlessly with the digital twin of the Cyprus power system within a hardware in the loop (HIL) environment. Additionally, the ABCM-T platform design should be fully compatible with the OneNet system, enabling standardized communication and seamless data exchange with various entities involved in the demonstration, such as the TSO energy market and large-scale FSPs.

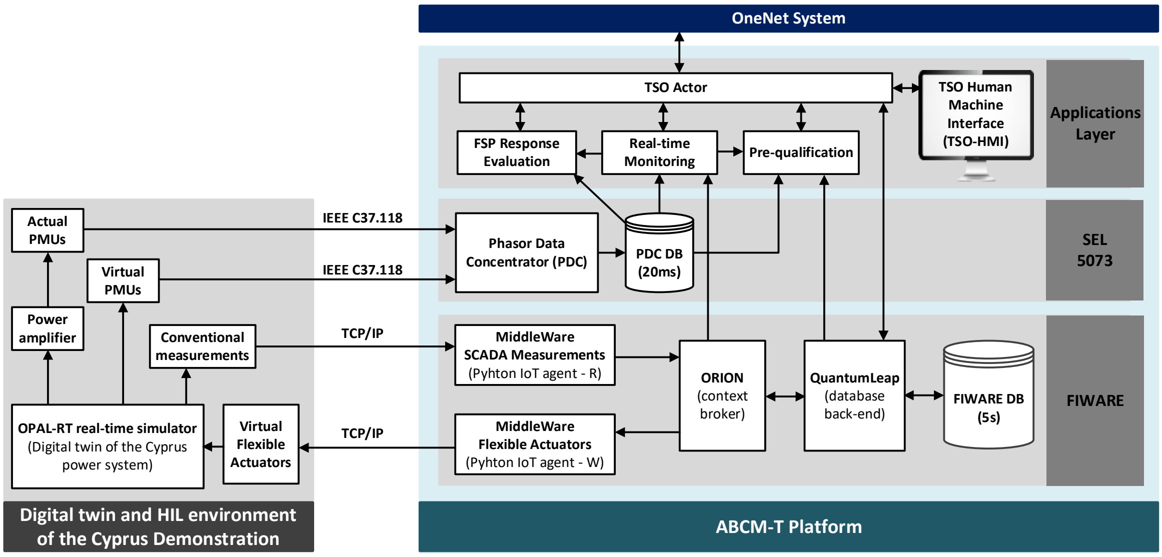

Figure 6: ABCM-T platform architecture

The ABCM-T platform requires the utilization of both actual and virtual PMUs to acquire measurements through the IEEE C37.118 protocol [18]. To facilitate this process, an industrial Phasor Data Concentrator (PDC) (SEL-5073) [21] is seamlessly integrated into the ABCM-T platform. The PDC enables the efficient reception of synchronized measurements from the PMUs every 20 ms, aligning the time stamps of these measurements, and securely storing them in its database.

To ensure adaptability and easy access to these important measurements, an Application Programming Interface (API) needs to be configured according to [21]. This API should allow the ABCM-T platform to effortlessly retrieve PMU measurements, whether it is the latest value or historical data. This retrieved data can be effectively utilized by various applications within the platform, such as the transmission grid real-time monitoring application, pre-qualification, etc. The integration of the PDC and the development of the API are required to enhance the ABCM-T platform's capabilities and provide a comprehensive solution for effective power grid management and decision-making.

The ABCM-T platform requires to manage conventional SCADA measurements and effectively coordinate the flexible resources virtually implemented within the digital twin of the Cyprus power system. To enable seamless information exchange, the TCP/IP protocol should be utilized to ensure measurement and coordination signals exchange between the platform and the digital twin every 5 seconds.

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For this purpose, two middleware solutions need to be designed and developed, as FIWARE IoT agents [23], [24] allowing bidirectional data exchange between the digital twin and the ABCM-T platform. These middleware components are required to facilitate the retrieval of measurements (read) and the transmission of coordination signals (write), enhancing the platform's operational efficiency. The conventional measurements are managed by ORION context broker [24] and QuantumLeap REST service [25] in order to be stored in a time-series database.

To further enhance the capabilities of the ABCM-T platform, an application layer needs to be developed on top of the two back-end systems (the PDC and FIWARE). Within this application layer, various tools and applications can be designed and created to enable the system use cases of the Cyprus demo. These applications need to obtain PMU or conventional measurements, whether the latest values or historical data. Hence, for retrieving PMU data from the PDC an API has been developed according to [21], while for obtaining conventional measurements from the time-series database through QuantumLeap an API has also been developed based on [26]. The applications to be designed and developed need to serve three primary purposes: (a) real-time monitoring of the transmission grid, (b) facilitation of the TSO pre-qualification process, and (c) evaluation of the FSPs' response while providing ancillary services.

To enable users' interaction and control, the TSO actor should utilize HMIs. Through these interfaces, the TSO can monitor the operation of its system, procure services, define location-based pre-qualification limits, and prepare reports to ensure adequate responses from market participants.

A harmonized communication and information exchange with other entities, such as market operators and market participants, should be facilitated through the OneNet system. This standardized approach ensures seamless and efficient collaboration among various stakeholders within the power system, promoting optimal functioning and decision-making. The protocol that is used for the communication of the platform with the OneNet system was REST API [8], while the information that was exchange between the different actors was included in .CSV files.

4.3.2 ABCM-D platform architecture

A dedicated platform, named ABCM-D, has been developed specifically for the DSO to effectively manage the distribution grid in the Cyprus demo. The architecture of ABCM-D is depicted in Figure 7, and is designed to cater to the unique requirements of the distribution grid and the distinct role played by the DSO within the TSO-DSO-Market-FSP collaborative framework demonstrated in the Cyprus demo of the OneNet project.

While there may be some similarities between the ABCM-T and ABCM-D platforms, the inherent differences in the transmission and distribution grids and the roles of TSOs and DSOs necessitate separate platforms to

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support their respective functions. The ABCM-D platform needs to operate in real-time and interact seamlessly with the digital twin of the Cyprus power system within a Hardware in the Loop (HIL) environment.

Within this environment, the platform should be able to receive actual and virtual smart meter readings, as well as virtual conventional SCADA measurements, provided by the digital twin and the HIL setup. In addition, the platform should effectively coordinate the small/medium-scale FSPs, which can be either virtual or actual flexible actuators, as considered in the digital twin or the HIL configuration. It should also have the capability to coordinate actual residential prosumers (as discussed in Section 7), when those are in the loop with the Cyprus power system digital twin.

The ABCM-D platform needs to be fully compatible with the OneNet system, enabling standardized communication and seamless data exchange (related to the energy and ancillary services processes) with various entities, such as the DSO local energy market, small/medium-scale FSPs, and the TSO (through ABCM-T). This compatibility is important to foster a harmonized collaboration among the stakeholders, ensuring optimized management and operation of the distribution grid within the larger energy ecosystem. The protocol that is used for the communication of the platform with the OneNet system was REST API [8], while the information that was exchanged between the different actors was included in .CSV files.

The seamless exchange of information between the digital twin of the Cyprus power system and the ABCM-D platform is required. This should be facilitated through an open-source backend platform powered by FIWARE [23]. Within the FIWARE system, middleware components need to be developed as IoT agents to enable the integration between ORION context broker [24] and the digital twin. These IoT agents are responsible for reading measurements from and writing coordination signals to the digital twin of the Cyprus grid. The efficient and

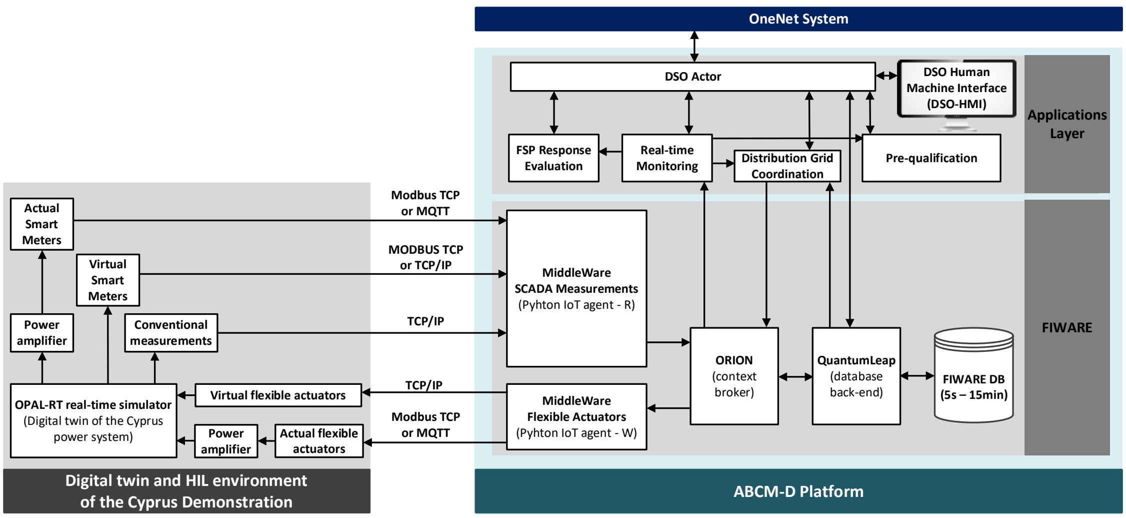

Figure 7: ABCM-D platform architecture

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effective management of the data needs to be handled by the ORION context broker [24], while QuantumLeap [25] should be utilized to store, query and retrieve data from a time-series database.

Then, to enable effective interaction between the backend system (FIWARE) and the application layer, a robust API needs to be developed according to [26]. This API serves as a link, allowing integration with all the necessary applications and tools required to enable the DSO-related system use cases during the demonstration. These applications within the ABCM-D platform retrieve smart meter or conventional measurements, whether the latest values or historical data, to enable various essential functions for (a) real-time monitoring of the distribution grid, (b) facilitating the pre-qualification process by the DSO, (c) evaluating the response of small/medium-scale FSPs, and (d) coordinating the distribution grid.

To ensure seamless control and monitoring, the architecture of the ABCM-D platform foresees visual Human Machine Interfaces (HMIs), allowing the DSO actor to interact with these applications. Through these interfaces, the DSO can effectively monitor the operation of the distribution grid, procure services to the local market, define location-based pre-qualification limits, prepare reports for market participant responses and coordinate all the flexible resources awarded by the local market in real-time to relieve congestion.

4.4 System use cases implementation

This section describes the implementation of the four system use cases (SUCs) of the OneNet project related to the Cyprus demo. These SUCs has been developed and integrated in the ABCM platforms to enhance the operational capabilities of the two operators (TSO and DSO) with emphasis on monitoring, pre-qualification, evaluation and coordination of the transmission and distribution grids to facilitate the effective operation of the Cyprus power system through the collaboration between the TSO and the DSO, through a new market framework, as presented in Section 5. The use cases of the Cyprus demo can be also found in [4] for more information.

4.4.1 Real-time monitoring

The monitoring of power systems is a key procedure for the operators since they can have a wide area visualization about the operating condition of the power system and can react promptly in case of a contingency [19]. The tool that is responsible for monitoring the operating condition of the power system is the state estimator, which processes the measurements that are reported from the substations of the power system. The state estimator can provide in consecutive time intervals the states of the power system, which are the voltage magnitude and angle for all the substations, given that the system is fully observable by the measurements arriving at the control center [20]. In the case of the Cyprus demo, the ABCM-T and ABCM-D platforms include a real time monitoring scheme applicable in the transmission and distribution systems respectively. The ABCM-

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T platform includes a monitoring scheme that relies on Phasor Measurement Unit (PMU) measurements, while the ABCM-D platform includes a monitoring scheme that processes smart meter measurements as well as power measurements. The two schemes will be briefly described below.

4.4.1.1 Real time monitoring scheme for transmission system

The real time monitoring scheme that was developed and included in the ABCM-T platform relies on the PMU measurements. The PMU is an advanced measuring device installed at the substation level and provided with high reporting rate voltage and current phasor measurements, frequency measurements, and rate of change of frequency measurements. The transmission level of the Cyprus power system is fully observable by PMUs which are installed in 18 substations. Through the information provided by the TSO of Cyprus and the Electricity Authority of Cyprus, the 18 PMUs were emulated in the Cyprus power system digital twin and PMU measurements were available by the exact 18 substations. The PMU measurements derived by the Cyprus digital twin power system are concentrated to the Phasor Data Concentrator (PDC), which time aligns the PMU measurements with the same time stamp from all the PMUs.

The PMU-based state estimator that was included in the ABCM-T platform is formulated in a Weighted Least Squares framework. Since the PMU measurements are linearly related to the states of the system [17], the PMU-based state estimator does not follow any iterative procedure and therefore can be executed in real time. Furthermore, the actual transmission grid parameters as provided by the TSO (i.e., line parameters, transformers tap ratio) are included in the state estimator Jacobian matrix. The procedure that is followed for the execution of the real time monitoring scheme is summarized below:

Step 1: Concentration of the PMU measurements: As the Cyprus power system digital twin runs in the real time simulator, the emulated PMUs in the 18 substations send measurements to the PDC that is installed in the ABCM-T platform through the IEEE C37.118 protocol [18]. It should be noted that the emulated PMUs are synchronized through a GPS signal that is provided in the real time simulation environment by the Oregano communication card installed in the real time simulator.

Step 2: Processing of the PMU measurements: The time aligned PMU measurements are concentrated in the database of the SEL 5073 PDC [21]. In order to fetch the PMU measurements to the PMU-based state estimator that was implemented in MATLAB software, an API was developed that is able to communicate with the database of the PDC and transfer the measurements to the PMU-based state estimator.

Step 3: Execution of the real time monitoring scheme: As soon as new PMU measurements arrive to the control center, the PMU-based state estimator is executed (every 20 ms) in order to provide in real time the operating condition of the power system. The states of the system for each execution of the state estimator are written to the database that is accessed by LabView where the GUI of the real time monitoring tool was developed.

In Figure 8, the interface of the real time monitoring tool that is included in the ABCM-T platform is presented. This interface is designed in LabView and can provide a multi-level view of the operating condition of the transmission and distribution systems. Figure 8, depicts the first level of the interface where the user can view general information regarding the transmission level based on the estimated states provided by the monitoring tool. In particular, as it can be seen in Figure 8, the single diagram of the Cyprus power system is available, while the user can see updated information regarding the system frequency, the conventional and RES generation, and the maximum and minimum voltages at the 3 level of the system (HV, MV, LV).

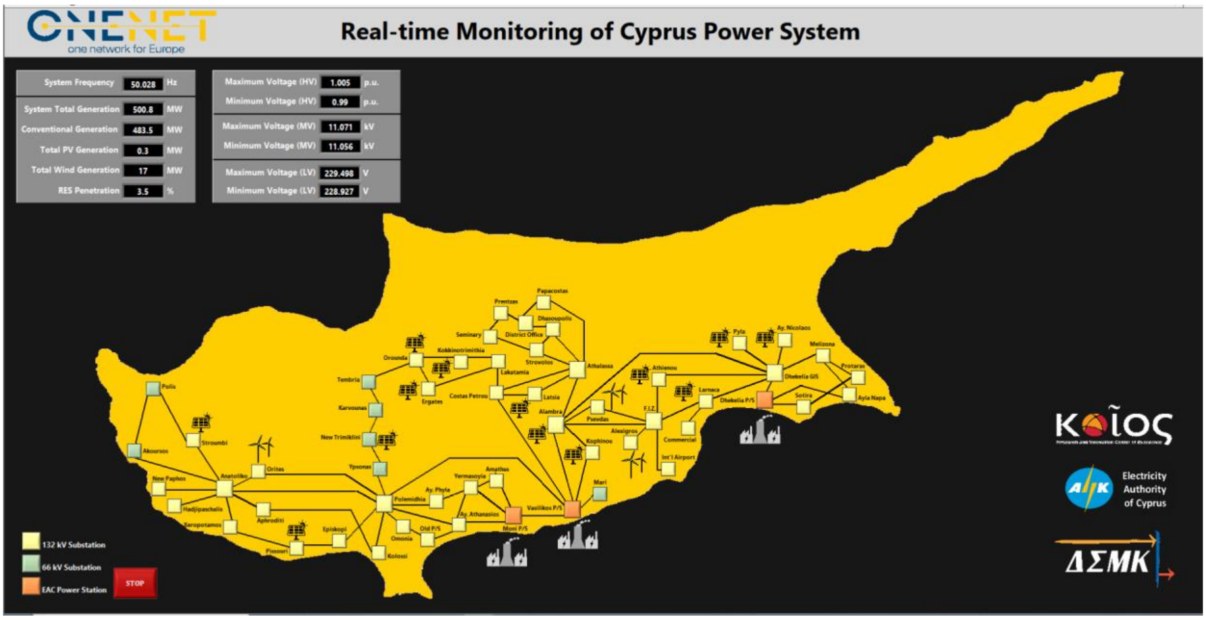

Figure 8: The first level of real time monitoring tool interface

The real time monitoring tool interface is interactive, and the user can click in any substation in order to view more details regarding the corresponding substations. Figure 9, shows the information regarding the Vasilikos power station that includes the voltage magnitude and angle of the Vasilikos substation and the neighbouring substations as they are provided by the PMU-based state estimator and the power flows of the lines that are connected to the substation, which are calculated by using the estimated states. Furthermore, in case that generators are connected to the substation, the tool can provide the actual generation that is provided to the system by the corresponding substation.

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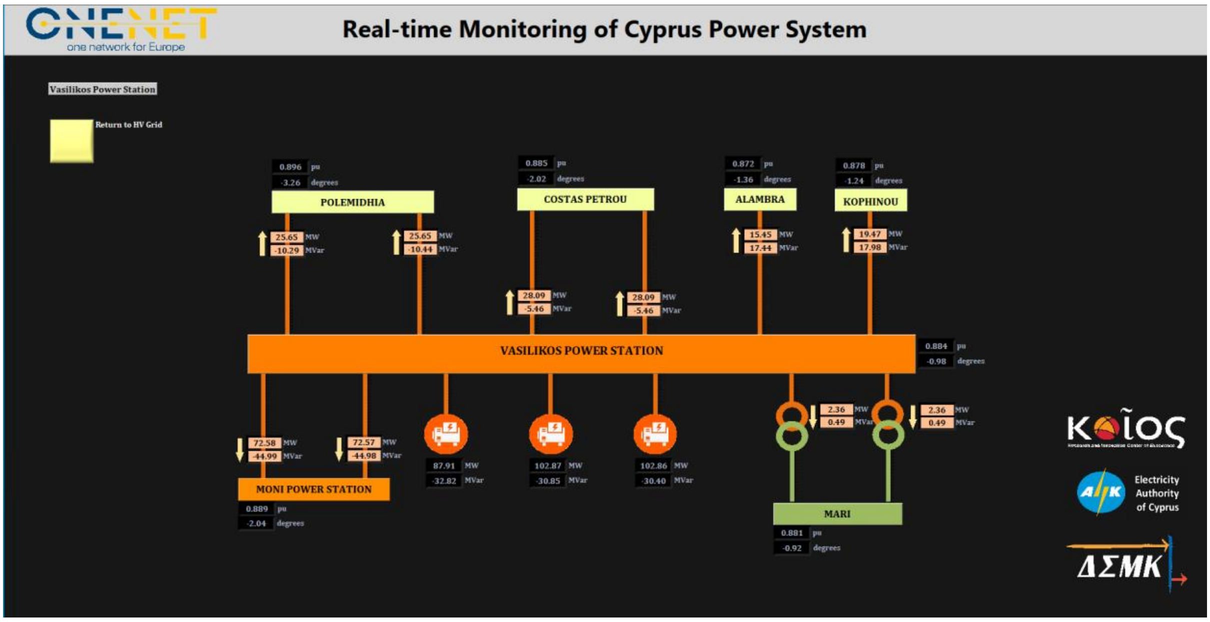

Figure 9: Monitoring of the Vasilikos power station

4.4.1.2 Real time monitoring scheme of the distribution grid

The real time monitoring scheme for the distribution grid is integrated in the ABCM-D platform in order to provide the operating condition of the distribution grid. The real time monitoring schemes for the medium and low voltage level of the distribution grid are formulated in a Weighted Least Squares framework using different grid configurations. In particular, the monitoring scheme for the MV level is based on the positive sequence network while the LV level considers a three-phase grid configuration.

Monitoring scheme of the MV level

The monitoring scheme of the MV level uses real and reactive power flows/injection measurements and voltage magnitude measurements from dispersed substations in the system. Since the measurements have a non-linear relationship with the states of the system, the MV level state estimator follows an iterative procedure to estimate the states of the power system [19]. The following procedure is followed for the monitoring of the MV power system:

Step 1: Concentration of the measurements: As the Cyprus power system digital twin runs in the real time simulator, the emulated measurement devices in the MV substations send measurements to the database of the ABCM-D platform through TCP/IP protocol.

Step 2: Processing of the measurements: The measurements that are concentrated in the database of the ABCM-D platform are used to the state estimator for the MV level that was implemented in MATLAB software, an API was developed that is able to communicate with the database of the ABCM-D platform and transfer the measurements to the MV state estimator.

Step 3: Execution of the monitoring scheme: As soon as new measurements arrive to the database, the state estimator is executed (every 5 s) in order to provide, in real time, the operating condition of the power system. The states of the system for each execution of the state estimator are written to the database that is accessed by LabView where the GUI of the real time monitoring tool was developed.

The interface of the monitoring tool that provides the operating condition of the MV level is shown in *Figure 10*. This is the third level of the real time monitoring tool interface where the user can enter by clicking to a corresponding interface between the HV/MV substation. As it is shown in *Figure 10*, the monitoring updates the voltage magnitude and voltage angle of the grid as well as the real and reactive power demand. Furthermore, the user can see the power flows from the MV lines, as well as the substations where RES are connected.

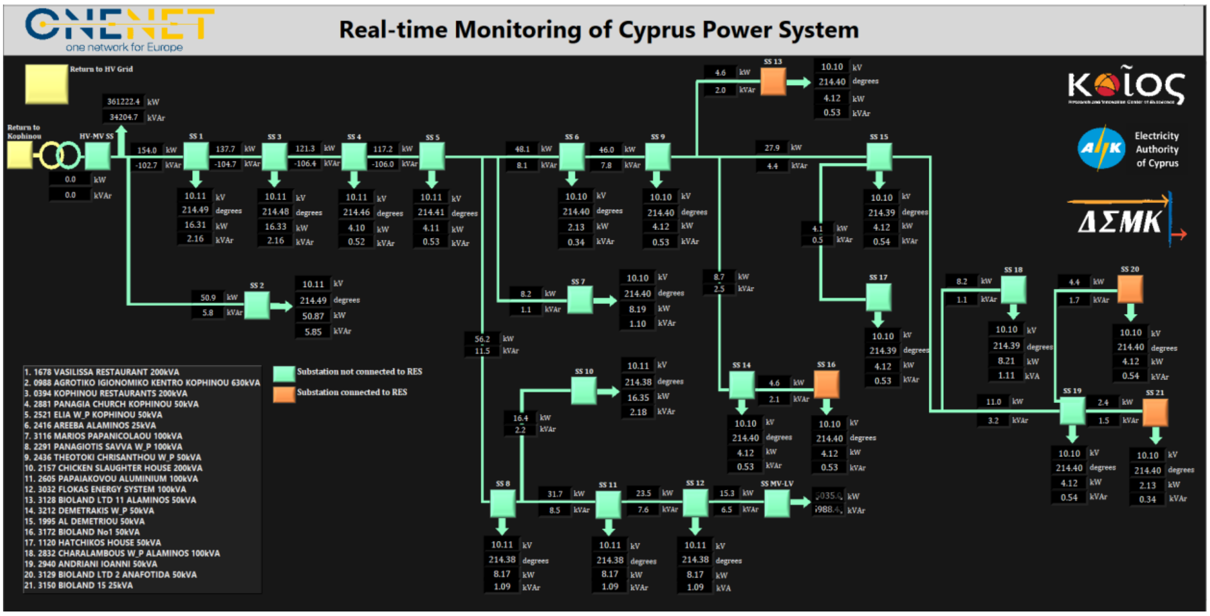

Figure 10: Monitoring of the MV grid

<u>Monitoring scheme of the LV level</u>

The monitoring scheme of the LV level is based on the smart meter measurements that are received for the consumers or prosumers. In this level, it is assumed that smart meters are installed in all the household consumers or prosumers of the LV feeder. The main difference of this monitoring scheme in comparison to the schemes for the HV and MV level grid is the three-phase configuration that is considered in the state estimator [22]. One of the main characteristics of the LV system is the unbalance conditions between the phases due to the presence of single and three phase loads. Thus, in the LV state estimation scheme the grid should be modelled in a three-phase configuration.

In this three-phase state estimation scheme, the formulation is based on the Weighted Least Squares framework. The main measuring equipment is smart meters which can provide the active-reactive power consumption of the consumers as well as voltage magnitude measurements. Thus, the state estimator follows again an iterative procedure. The following procedure is followed for the monitoring of the LV network:

Step 1: Concentration of the measurements: As the Cyprus power system digital twin runs in the real time simulator, the emulated smart meters in the LV nodes send measurements to the database of the ABCM-D platform through TCP/IP protocol.

Step 2: Processing of the measurements: The smart meter measurements that are concentrated in the database of the ABCM-D platform are used to the three-phase state estimator for the LV level that was implemented in MATLAB software, an API was developed that is able to communicate with the database of the ABCM-D platform and transfer the measurements to the LV state estimator.

Step 3: Execution of the monitoring scheme: As soon as new measurements arrive to the database, the state estimator is executed (every 10 s) in order to provide, in real time, the operating condition of the power system. The states of the system for each execution of the state estimator are written to the database that is accessed by LabView where the GUI of the real time monitoring tool was developed.

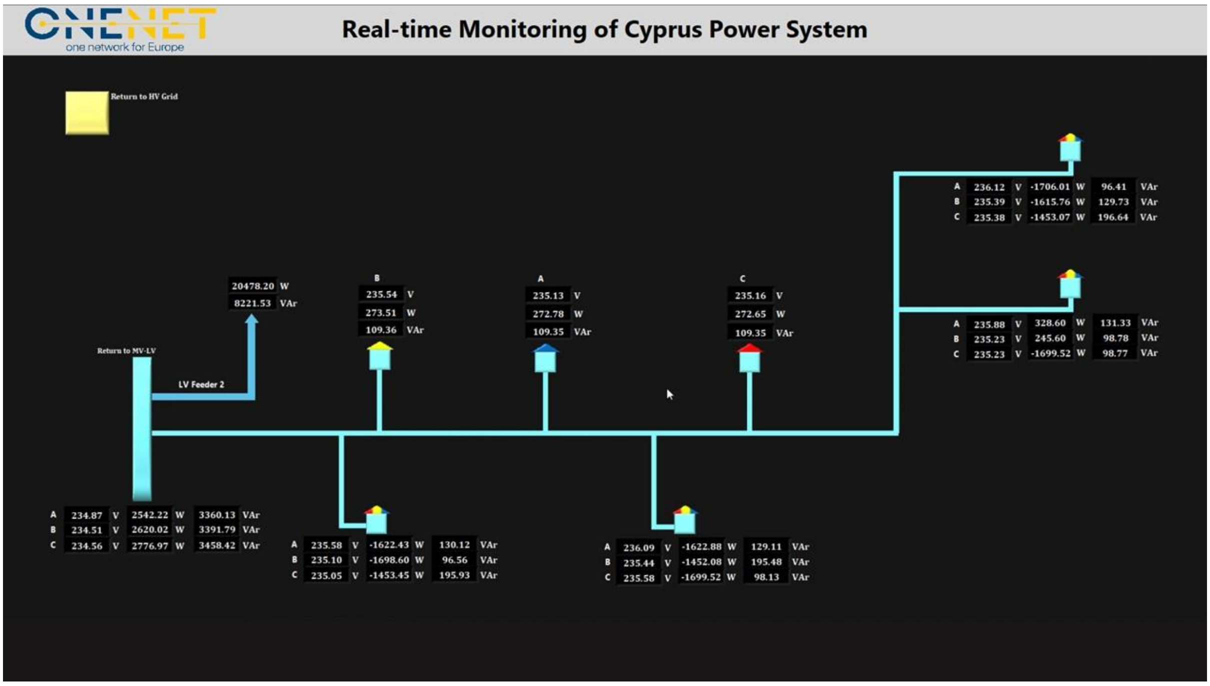

Figure 11: Monitoring of the LV grid

The interface of the monitoring tool for the LV grid is shown in *Figure 11*, which is the last level that the user can navigate through. In the monitoring tool for the LV grid the voltage magnitude and the active and reactive power consumption of the prosumers per phase can be monitored.

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4.4.2 Pre-qualification

The prequalification scheme is a very important tool in order to ensure that the distribution grid operational limits will not be violated with the participation of the FSPs, located at the distribution system, to the Intra-Day TSO Frequency Containment Reserve market. The prequalification tool calculates the available limits for each HV substation (of the transformers in the HV/MV interface) using historical data for each hour. The forward and reverse prequalification limits (active power) for each substation are sent to the Intra-Day TSO Frequency Containment Reserve market to be considered in the clearing procedure of the market. Forward limits are the limits that correspond to the nominal flow direction (i.e., from high to low voltage levels), while reverse limits correspond to the reverse flow (i.e., low to high voltage level).

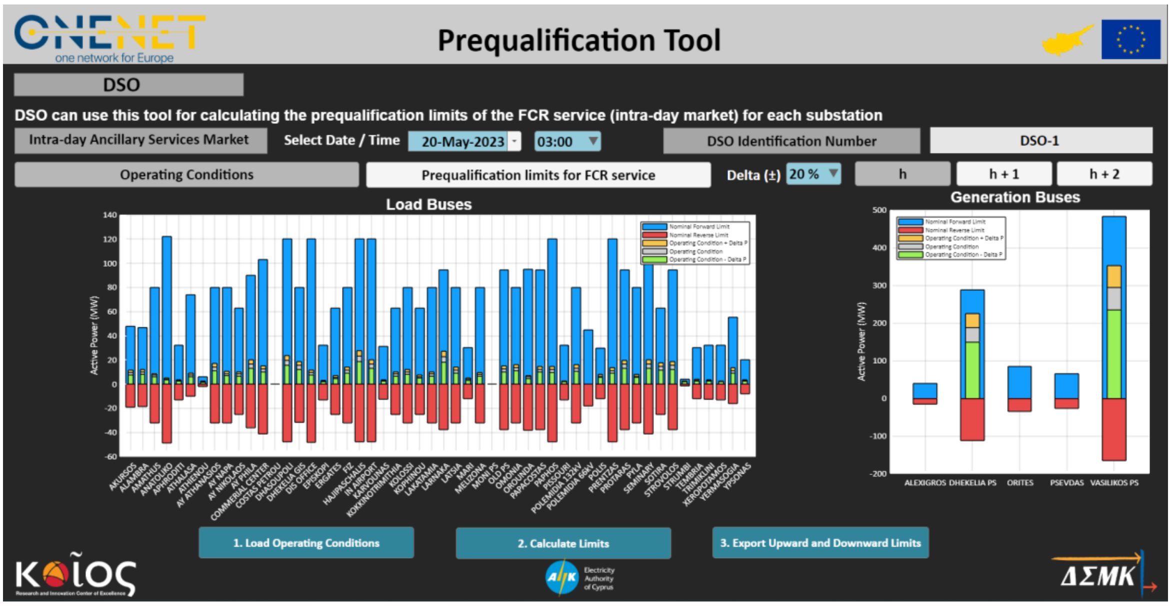

Figure 12: Graphical Interface of the Prequalification Tool – Prequalification limits for FCR service

For the purposes of pre-qualification, a Graphical Interface (GI) tool was developed within the App Designer, as illustrated in Figure 12. This tool retrieves data through the ORION context broker and, following a series of processes, extracts the operational limits of each substation for the specific time point of analysis. The operation procedure can be described with the following steps:

Step1: By clicking the "1. Load Operating Conditions" button, this tool loads information about the nominal operating values of each substation. It also fetches measurements (i.e., active and reactive power) for each substation that are related to the current operation of the transmission system from ORION.

Step 2: Subsequently, upon clicking the "2. Calculate Limits" button, the operational range of each substation for the next 3-hour period is computed, incorporating a tolerance limit (Delta). This limit is used for compensating any uncertainty encompassed to the historical data used for extracting the operating conditions

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of the substations, and it has predefined values from 5% to 20% with steps of 5%. The user can see the prequalification limits for each of the next three hours by choosing the tab for a specific time-period on the tool interface (h, h+1, and h+2), and the corresponding graphs for that period are displayed after selecting the "Prequalification limits for FCR service" window.

Step 3: The user can also see the operating condition of each substation by clicking the "Operating Conditions" option, as shown in Figure 13.

Step 4: Finally, by clicking the "3. Export Upward and Downward Limits" button, the maximum and minimum limit values for each bus are exported and forwarded to the OneNet system. These values are then incorporated to the clearing algorithm of the Intra-Day TSO Frequency Containment Reserve market in order to ensure that the operational limits of each substation are not violated when the FSPs (in the distribution system) provide frequency support services to the grid.

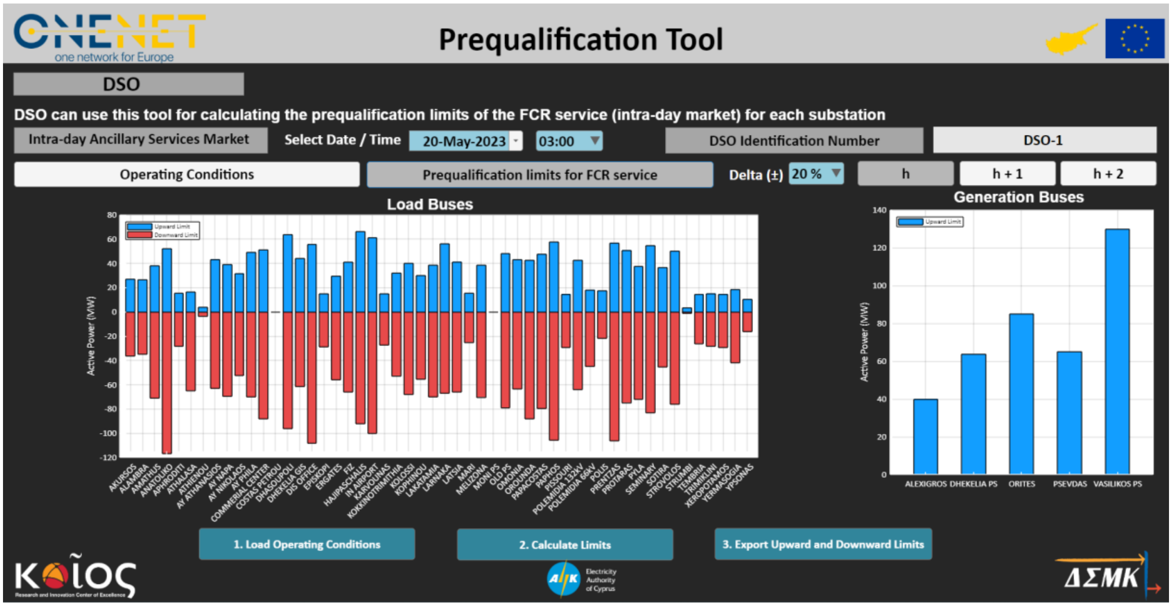

Figure 13: Graphical Interface of the Prequalification Tool – Operating conditions

4.4.3 FSP response evaluation

The third SUC that has been developed for the Cyprus demo focuses on assessing the response of FSPs, considering services cleared by the market and the automatic activation of these services by the grid conditions or the manual activation by the grid operators. With this tool, the TSO and the DSO can analyse the response of FSPs to extract valuable insights for technical and administration purposes, evaluating the capability of each FSP to respond to market and operators demands. The tool can also be used for compensation/payment purposes, in cases where FSPs fail to respond correctly.

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The FSP evaluation tool has been developed using MATLAB's App Designer for implementing a software with a graphical user interface, as presented in Figure 14. For evaluating the effective response of the FSPs to provide ancillary services, two main functionalities are needed by this specific tool, as described below and indicated in the GUI of Figure 14.

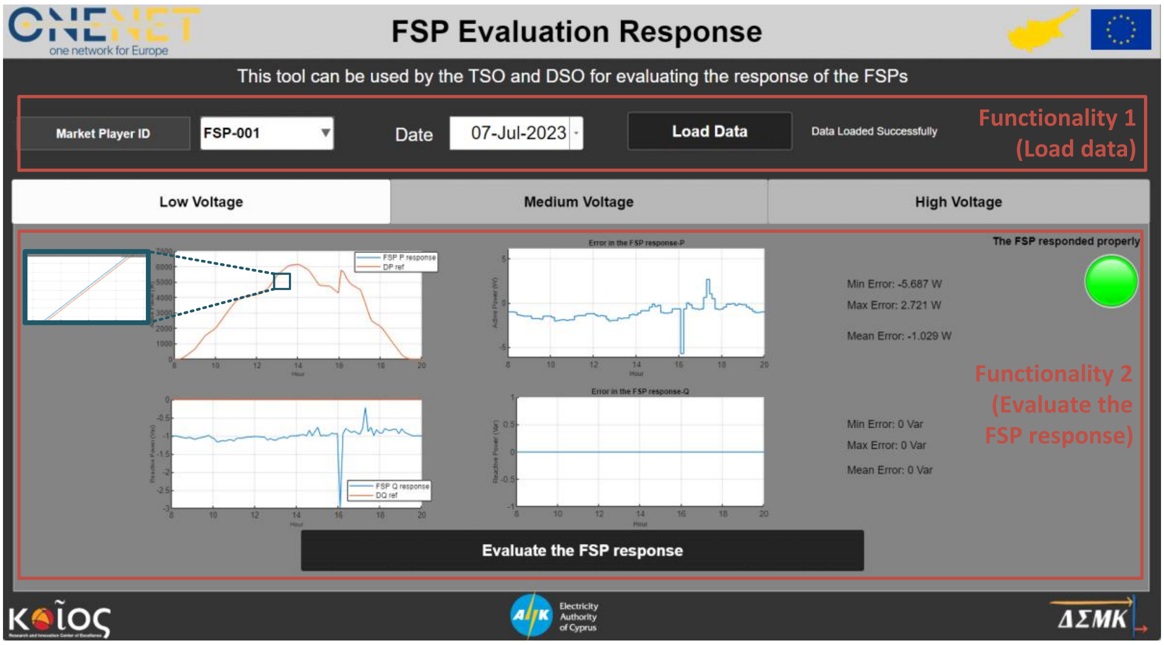

Figure 14: Graphical Interface of the FSP Evaluation Response

- **Functionality 1 – Load required data for the evaluation:** For evaluating the response of the FSPs the necessary data needs to be loaded. Thus, in this functionality level, the user first selects the FSP to be assessed, by selecting from the list the FSP's market player identification (ID) number. Then, the user needs to select the date for which the assessment will be performed and by pressing the "Load Data" button, the tool retrieves all the necessary data from the OneNet system that will be used for the evaluation of the specific FSPs. The loaded data contains the market clearing results and the response of a specific FSP (actual measurements regarding the FSP operation) for the time window under assessment. Furthermore, depending on which market the FSP was participating, different data are needed. For example, to evaluate the FSP participation in the near real time local DSO ancillary services market (low or medium voltage), the coordination signals sent by the DSO to manually activate the FSP's ancillary services are needed for the evaluation phase. On the other hand, for evaluating FSPs participating in the intra-day TSO frequency containment reserve market, since the provision of ancillary services is automatically activated/triggered by the grid condition, a high-resolution dataset regarding the grid frequency before, during and after a grid disturbance is needed to evaluate if the FSP has reacted properly. After pressing the "Load Data" button, if all the necessary data for the evaluation of the specific FSP for the specific date have been found, then a

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corresponding message (Data Loaded Successfully) is displayed in the GUI. Otherwise, the tool informs through the GUI that no data were found (Problem: No Data Found).

- **Functionality 2 – Evaluate the FSP response:** The second functionality of this tool is to analyse the data loaded (in functionality 1) in order to evaluate the FSP response. By clicking the "Evaluate the FSP response" button, the tool analyses the loaded data and generates graphical representations (time-series plots) and numerical indicators (i.e., mean error, minimum error, maximum error) to indicate if the response corresponds properly to the market clearing results and the activation signals. It should be clarified that in the example of Figure 14 for evaluating the FSP response according to the ΔP_{ref} and ΔQ_{ref} coordination signals by the DSO, only the non-zero DSO coordination signals are taken into consideration to evaluate the FSP response. Thus, in the example of Figure 14, since the reactive set-point by the DSO is always at zero, the evaluation does not perform for the reactive power. However, since the active power coordination signal is not zero during the time window of this investigation, the evaluation is performed indicating that the FSP can very accurately track the coordination signal sent by the DSO. In general, according to the results of this tool, an indicator pops up as a "green light" when the FSP responded properly within the evaluation time window, while a "red light" pops up when the FSP response is not within the acceptable margins.

It should be noted that the FSP evaluation response tool (Figure 14) is equipped with different interfaces for FSPs participating in either low, medium or high voltage grid level, while a different evaluation is also performed for different ancillary services (e.g., provision of frequency containment reserve, provision of active/reactive power flexibility for congestion management, etc.). Hence, the user can navigate at the corresponding voltage-level and type of ancillary service to evaluate the FSP response and observe the result of the evaluation.

4.4.4 Distribution grid coordination

The fourth SUC of the Cyprus demo emphasizes on the automatic coordination of the distribution grid in order to relieve congestion, especially forward and reverse overloading conditions in both the medium (MV) and low (LV) voltage distribution grids. To achieve this, the flexibility of the medium and small scale FSPs connected in the distribution grid needs to be exploited through a new ancillary services market scheme (as defined and developed in Section 5).

In this context, an automatic distribution grid coordination tool has been developed (and integrated within the ABCM-D platform) to generate the coordination signals for provisioning ancillary services by the FSPs to relieve congestion. In the Cyprus demo, the following ancillary services have been considered as flexibility services for congestion management:

- Upward active power (ΔP) flexibility services provided by Battery Energy Storage Systems (BESSs),
- Downward active power (ΔP) flexibility services provided by BESSs and Photovoltaic (PV) inverters,

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- Upward and downward reactive power (ΔQ) flexibility services provided by BESSs and PV inverters,
- Phase balancing compensation services, defined as negative and zero sequence apparent power provided by FSPs' inverters with capabilities for asymmetric current injection [27]-[28].

It should be noted that phase balancing is an ancillary service able to symmetrize the per phase loading conditions, and it has been defined in recent standards [29]. Such a service allows equal distribution of loading conditions per phase in transformers, cables and lines of the distribution grid, enabling maximum utilization of the available grid capacity. Therefore, this is an essential service to relieve congestion [30], especially in LV-MV distribution grids where the asymmetric loading conditions are quite intense. Additionally, active and reactive flexibility services are also considered by BESSs and PV inverters of the FSPs in order to manage congestion either under forward overloading conditions during the afternoon (peak loading conditions) or under reverse overloading conditions during noon (peak generation by distributed resources). The innovative part of this coordination tool is that the congestion is managed in the distribution grid by considering the available ancillary services cleared by the near real time market (Section 5.1.2.3), while minimizing the DSO market cost for activating the ancillary services to relieve congestion.

4.4.4.1 DSO procures flexibility services for congestion management

Since the near real time local market for ancillary services (Section 5.1.2.3) clears every 1 hour, the DSO should be able to pre-evaluate the expected loading conditions per HV/MV substation (or per MV feeder), or per ML/LV substation (or per LV feeder) in order to decide if ancillary services for congestion management are needed for that specific time window. If ancillary services are needed, then the corresponding services should be procured in the near real time market for the next 1-hour time interval.

The pre-evaluation of the expected loading condition is performed by analysing historical time-series data (with 5- or 30-seconds resolution) for the time-window of interest considering a number of previous days with similar characteristics (e.g., weekend or weekdays). From this analysis the average maximum loading conditions (for forward power flow) and the average minimum loading conditions (for reverse power flow) are extracted per 1-hour timeframe (same time frame with the ancillary services market). It should be noted that the average maximum/minimum is determined by calculating first the maximum/minimum conditions for a 1-hour time window per day, and then averaging the maximum/minimum for the number of days under consideration. An additional uncertainty margin (e.g., 5%, 10%) is added/subtracted to/from the average maximum/minimum loading condition to deal with the worst-case deviation from the historical analysis datasets, in order to calculate the expected maximum/minimum loading conditions for the time-window of interest. If these expected maximum/minimum loading conditions exceed the grid limits (e.g., transformer limits), then ancillary services need to be procured to the near real time market in order to allow the DSO to use this flexibility during the actual operation for congestion management.

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Market procurement by the DSO is performed by considering an analytical algorithm that has been derived, which generates the best combination of ΔP and ΔQ services that can be used to relieve congestion, while ensuring the minimum cost for the DSO. This algorithm requires the estimation of the clearing prices for ΔP and ΔQ services (calculated as average availability clearing cost for these services) and the worst-case loading conditions (expected maximum/minimum loading conditions - active and reactive power) in order to calculate the combination of services that can be used to avoid overloading conditions and those values are actually procure to the near real time market by the DSO for the specific substation and for the specific time-window (ΔP^{proc}, ΔQ^{proc}). In case the asymmetric loading conditions are quite intense in a particular part of the distribution grid, and if there are connected FSPs with capability for asymmetric current injection, then the DSO can also procure services for phase balancing, as negative or zero sequence apparent power (S_{neg}^{proc} or S_{zero}^{proc}) in order to fully or partially symmetrize the loading conditions as an extra measure to manage congestion (and improve power quality at the same time).

4.4.4.2 Coordination of distribution grid by activating ancillary services

After the DSO procures the ancillary services bids needed to relieve congestion and after the FSPs place their generation offers, the near real time market will clear and inform all the relevant parties about the market results. At this stage, the DSO knows the available capacity of ΔP, ΔQ and phase balancing (PB) services at each part of the distribution grid (per substation) and can proceed with the real-time operation and coordination of the grid to ensure that any over-loading conditions will be properly and timely managed. On the other hand, the FSPs awarded for these specific ancillary services are paid in order to be available to provide those services upon activation by the DSO in case of overloading conditions.

It is noted that the FSPs are paid for the availability (commitment to provide the service if activated) and they are additional paid for activation when the DSO activates them to provide an amount of each service. In the Cyprus demo, the additional activation cost for ΔP is equal to the day-ahead energy price, while the activation costs for ΔQ and PB have been considered as percentages of the day-ahead energy price (i.e., 20% for ΔQ and 23% for PB). Thus, even though the DSO may procure ancillary services for covering the worst case expected conditions, in case an overloading does not occur during operation, the DSO should not activate the ancillary services to avoid paying the additional activation cost.

Now, the development of the coordination tools for managing congestion in the distribution grid relies on real-time measurements received from the substation (either HV/MV or MV/LV) and from the available FSPs connected downward of the specific substation. Those measurements are analyzed, and if overloading conditions are identified, coordination signals for activating corresponding ancillary services are generated and allocated to the FSPs in order to timely manage congestion, as shown in Figure 15.

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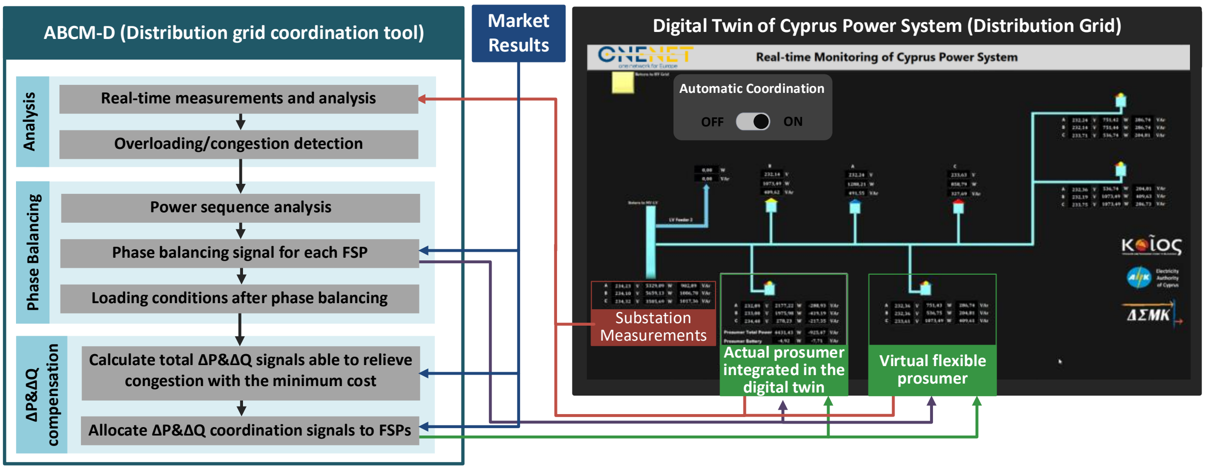

Figure 15: Online coordination of distribution grid digital twin by the ABCM-D platform.

The main steps of the developed coordination tool for distribution grids are described below. Please note that the coordination tool is executed in a periodic manner. A 60 seconds constant period is considered for the coordination tool of the Cyprus demo, however the control period can be reduced (to achieve a faster controller), as soon as the control period is larger than double the period of the slower sampling measurement rate, in order to ensure stability. The coordination tool is described in the following 7 steps:

- **Step 1 - Real time measurement and analysis:** The DSO algorithm continually measures the real-time loading conditions at the substation level, related with active and reactive power flows as well as voltage per phase. Similarly, real-time measurements regarding the FSPs' operating conditions are also needed. Those measurements are taken periodically (e.g., every 5 seconds for SCADA measurements, and every 30 seconds for FSP measurements from fast reporting smart meters) from the digital twin of the Cyprus power grid and are stored in the time-series database of the ABCM-D platform. Hence, the developed tool starts with the retrieval of the last value (from the database) regarding the active and reactive power of the substation and of the downward connected FSPs. Then, the algorithm subtracts the DP, DQ contribution (total contribution from all the FSPs) from the substation loading condition in order to identify the pure net loading conditions without the FSP response.
- **Step 2- Overloading/congestion detection:** The pure net loading condition is used to check if there are any overloading condition that need to be compensated. If there are no overloading conditions, then zero coordination signals are sent to the FSPs, in order to minimize the activation cost for the DSO. Otherwise, the algorithm needs to continue to estimate the PB, ΔP and ΔQ coordination signals required to manage congestion.
- **Step 3 - Power sequence analysis:** Steps 3-5 are only performed if PB services are available to symmetrize the loading condition. An important step to coordinate the phase balancing services is to analyse first the asymmetric loading condition at the substation level. Thus, the pure net loading

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condition of the substation (without the contribution of FSPs) is analysed into its positive, negative, and zero sequence power components.

- **Step 4 – Phase balancing coordination signal for each FSP:** From the power sequence analysis of Step 3, the positive sequence component corresponds to the symmetrical power operation, while the negative and the zero sequence components correspond to the asymmetrical operation to be compensated through the coordination of the phase balancing scheme. Hence, the negative and zero sequence power components need to be locally produced by the FSPs in order to compensate the loading asymmetries at the substation level, allowing equal utilization of the existing grid capacity. Thus, if the amplitude of the required negative/zero power needed for full compensation is within the available capacity for PB, then a full compensation can be achieved, otherwise a partial compensation can be achieved considering the maximum available capacity of the FSPs for PB. The coordination signal to be sent to the FSPs contains the angle of the negative/zero sequence power (common for all the FSPs) and the amplitude of the negative/zero sequence power (calculated according to a weighted approach based on the total availability cleared and the availability cleared for each FSP by the market).
- **Step 5 – Loading conditions after phase balancing:** After phase balancing control is completed, the remaining loading conditions are recalculated to check if congestion management control is still needed at the substation level, according to the upper and lower limitations of the transformer. This is achieved by transforming (from sequence to phase) the PB coordination signals (calculated in Step 4) and then add the phase power component of the PB to the pure net loading conditions of the substation (calculated in Step 1). Then, the algorithm checks for remaining overloading conditions to be compensated in Step 6 and Step 7. It is noted that since the analysis is performed per phase, the congestion is managed in a per phase approach since it is important to ensure the thermal capacity limit at each phase in a distribution grid with intense asymmetries is maintained.
- **Step 6 – Calculate total ΔP & ΔQ signals able to relieve congestion with the minimum cost:** In this step, the required ΔP and ΔQ services to be activated to relieve the remaining congestion (after phase balancing) are calculated. The calculation is performed for the most congested phase (if a full symmetrisation of the loading condition was not possible in Steps 3 – 5) to ensure that all three phases are within the thermal limits of the transformer. An algorithm (based on an analytical solution), similar to the one developed for the procurement of ΔP and ΔQ services with the minimum cost (in the previous subsection), is also used here to identify the best combination of ΔP and ΔQ services (total active and reactive deviation) needed to avoid overloading condition with the minimum cost. In this case the activation cost (and not the availability cost that has been used in the case of the procurement) and the real-time active and reactive power (and not the worst-case active and reactive power) are taken into account to calculate the best combination of active and reactive flexibility services needed to manage congestion.

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- **Step 7 – Allocate Δ*P* & Δ*Q* coordination signals to FSPs:** The final step is to calculate ΔP and ΔQ coordination reference signals to be allocated to each FSP. This is performed in a weighted manner considering the total and the per FSP availability cleared by the market during the specific time window. The final coordination signals Δ*P*, Δ*Q* and PB are sent to the FSPs emulated or integrated within the Cyprus power system digital twin (in a periodic manner, every 60 seconds) in order to provide those ancillary services and relieve congestion.

4.4.4.3 Pre-validation of the coordination

After developing the coordination algorithm, a pre-validation has been performed to ensure the proper operation of the automatic coordination tools under different grid conditions. Figure 16 validates the coordination scheme of ancillary services to relieve congestion, when (a) phase balancing is also used and (b) without using the phase balancing services. In this validation process, random loading conditions and random phase balancing, DP and DQ costs and available capacity have been assumed.

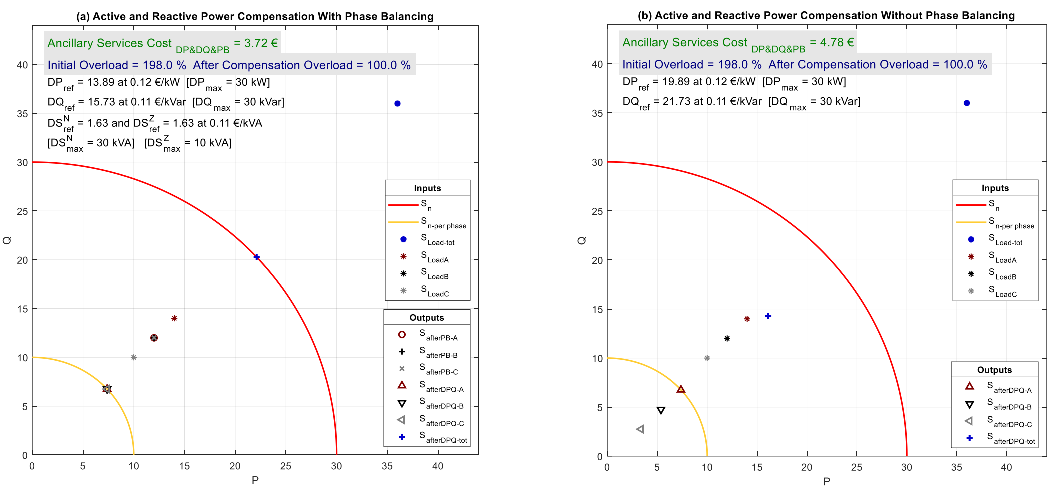

Figure 16: Pre-validation of the coordination tool where ΔP, ΔQ and PB services are regulated in real time to relieve congestion. The pre-validation results are presented (a) with PB and (b) without PB.

Figure 16(a) presents the validation of the ΔP and ΔQ coordination scheme when the phase balancing option is enabled. The validation results are presented in a P-Q plane. The initial substation loading conditions ($S_{LoadA/B/C}$) are presented where it is clear that the loading condition are not equally allocated to the three phases. However, after applying phase balancing, the per phase loading conditions ($S_{afterPB\text{-}A/B/C}$) are equally allocated to each phase, indicating that fully symmetrical loading conditions have been achieved after the phase balancing. Then, Δ*P* and Δ*Q* services are calculated and applied, where it can be observed that the loading conditions after the congestion management ($S_{afterDPQ\text{-}A/B/C}$) are equal to the thermal limit of the substation, relieving in this way the

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overloading conditions that occurred. This has been achieved by regulating ΔP, ΔQ and PB services while ensuring a minimum activation cost for the DSO.

Similarly, Figure 16(b) presents the validation of the ΔP and ΔQ coordination scheme without the phase balancing service. In this case, since the phase balancing option is not available, the coordination scheme should compensate the initial loading conditions ($S_{LoadA/B/C}$) considering the worst-case phase (most loaded phase – phase A). By compensating the most loaded phase, the other phases will also be relieved. ΔP and ΔQ services are calculated and applied, where it can be observed that the loading conditions after the congestion management ($S_{afterDPQ\text{-}A/B/C}$) ensure that all phases are within the thermal limits of the substation. Indicatively, the most congested phase lies exactly at the transformer limits, while the other phases are somewhat overcompensated since the phase balancing option is not available in this example. Hence, the congestion has been successfully managed through the coordination scheme by regulating ΔP and ΔQ, while ensuring a minimum activation cost for the DSO. Through this pre-validation process, we have ensured the proper response of the coordination scheme before proceeding to its final integration in the ABCM-D platform.

4.5 ABCM-T and ABCM-D platforms development and integration

This section focuses on the development and integration of the ABCM-T and ABCM-D platforms. The software development of the two platform has been performed according to the functional requirements and the architecture described in Section 4.2 and Section 4.3 respectively. The software development started from the backend software platform (FIWARE), by configuring the context broker (ORION), the database interface (QuantumLeap), and the time-series database. The required middleware for interconnecting the back-end software with the digital twin has been developed, along with a Python-based IoT agent to read/write data from/to the digital twin. In addition, a commercial phasor data concentrator from SEL [21] has been installed and configured in the server to allow the concentration of PMU data from actual PMUs (installed in the field or in a HIL configuration) and from virtual PMUs (integrated within the digital twin).

Then, the different SUCs have been developed as software applications, as described in Section 4.4, and they have been integrated with the ABCM-T/D platform. The integration has been facilitated through the development of APIs, providing these applications with a standardized interface to read last values or historical data (that are processed according to the needs of each application) and write the coordination signals to be sent to the digital twin to effectively coordinate the operation of the power system. The proper interfaces have also been developed for each SUC, allowing users to have a visual interface to monitor the operation of the transmission and distribution grids in real time, pre-qualify the capacity of specific ancillary services according to the power system operating conditions, coordinate in an automated manner the operation of the distribution grid, and evaluate the proper response of the FSPs during the provision of ancillary services.

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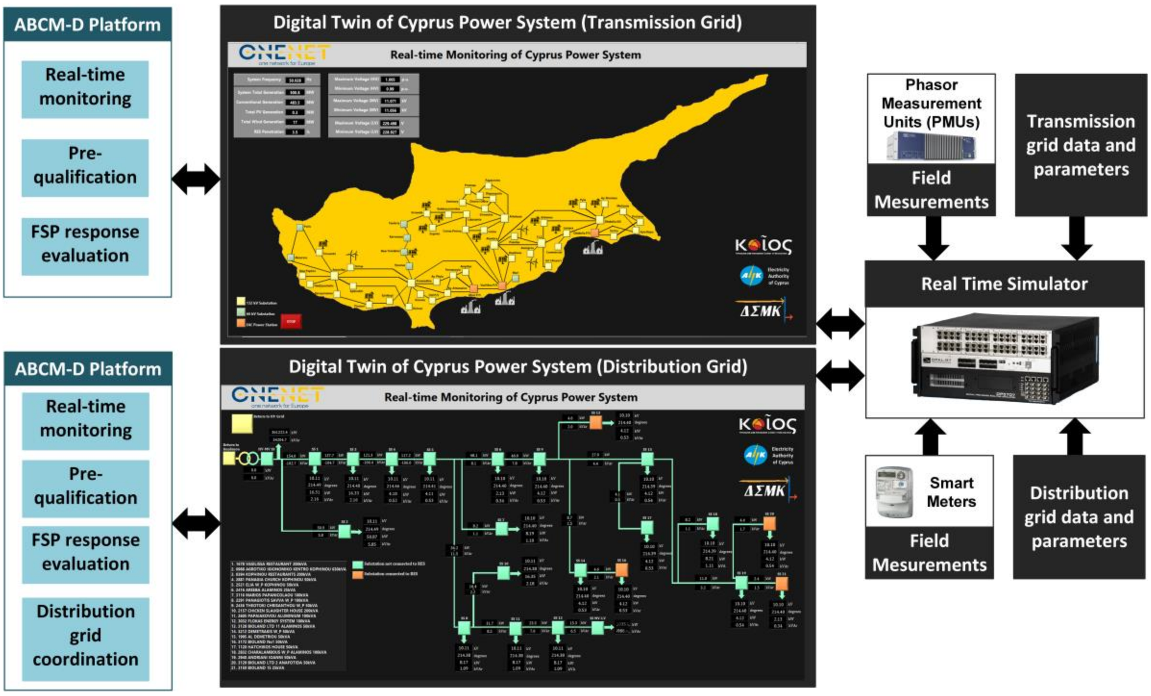

Figure 17: Development of the ABCM-T and ABCM-D platforms, where the SUCs have been integrated and integration with the Cyprus power system digital twin through a control-HIL configuration has been achieved.

After the development of the two platforms and the integration of the developed SUCs within the platform, the next step is related to the integration of the digital twin and the platform, as illustrated in Figure 17. The digital twin of the Cyprus power system has been developed and described in Section 3. The digital twin is executed in the RTS, which is equipped with dedicated communication cards allowing the exchange of data with the ABCM-T/D platforms through the use of digital communication protocols (e.g., TCP/IP, Modbus TCP, etc.). Hence, proper communication interfaces have been configured within the digital twin to enable the seamless exchange of data with the back-end middleware (Python-based IoT agents). Therefore, the periodic and bidirectional exchange of data is facilitated between the digital twin and the ABCM-T/D platforms, allowing a control-HIL framework to validate and demonstrate the solutions developed for the Cyprus demo, as shown in Figure 17.

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5 Design and Development of an Ancillary Services Market

One of the main objectives of the OneNet project is to facilitate the seamless coordination between TSO, DSO, FSPs, and prosumer as a pathway to enhance the operational capabilities of the grid, allowing higher penetration of RES. To achieve this, FSPs and prosumers should actively participate and support (e.g., provision of ancillary services) the operation of the grid according to TSO and DSO needs, while contradictory actions of one operator (e.g., DSO) that may affect the other operators (e.g., TSO) should be avoided. In this context and to facilitate an effective coordination between all key entities, a new ancillary services market framework is needed. Hence, within the Cyprus demo of the OneNet project, a new market framework has been designed and developed, enabling the provision of ancillary services by large-, medium- and small-scale FSPs for increasing the economic benefits of FSPs and improving the congestion management capabilities and stability of modern power grids. This section describes the design and implementation of the new market framework developed for the Cyprus demo.

5.1 New Ancillary Services Market design

In general, the electricity market encompasses a series of processes aimed at selecting suitable energy producers to effectively address the energy needs of consumers in a way that is efficient, optimal, and cost-effective. These operations are overseen by specific market operators, namely the Global TSO Market for the transmission level and the Local DSO Market for the distribution level. Participation in the electricity market settlement usually takes place in three phases: 1) day-ahead, 2) intra-day, and 3) near-real-time market. In this section, the overall market framework considered for the Cyprus demo is described, as presented in Figure 18.

5.1.1 General market framework of the Cyprus demo

5.1.1.1 Day-Ahead market

The initial phase of the market (Day-Ahead) focuses on energy balancing, where energy producers declare their available generation capacity and prices (generation offers), while retailers specify the corresponding demand and prices (demand bids) for a full 24-hour period, one or few days before the planned scenario, with a time resolution determined by the market scheme (e.g., 1-hour). At this stage, the Global TSO Market gathers all relevant data and finalizes the quantities of energy production and consumption (clear the market) at an optimal price to maximize Social Welfare. Subsequently, it communicates the settlement outcomes to all the interested parties (e.g., retailers, producers, TSO).

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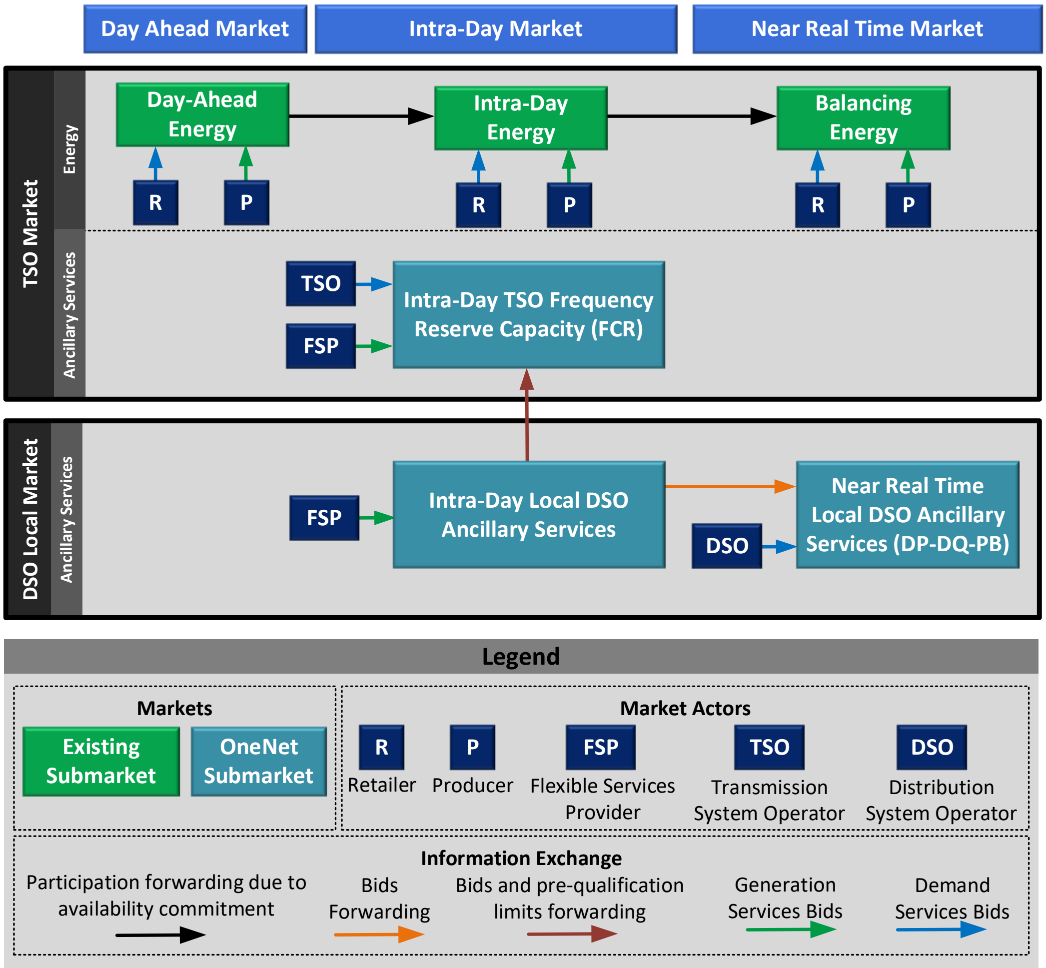

Figure 18: Energy market framework for the Cyprus demo.

It should be clarified that usually this day-ahead market exists in most of the countries and thus, the Cyprus demo considers this as an existing market without introducing any changes.

5.1.1.2 Intra-Day market

In the second phase (Intra-Day), the market may emphasize on both energy balancing and ancillary services coordination. The Intra-Day Energy market handles the power imbalances, due to deviations from the day-ahead committed values. Such power imbalances may occur due to updated forecasting by RES. It should be noted that usually there is not a clearing mechanism for the energy intra-day market, and it simply relies on financial contracts to be agreed bilaterally between each pair of buyers and sellers. These contracts are handled through a central platform.

Beside the Energy Intra-Day market, the intra-day market level can also be enhanced with ancillary services, in either global TSO or local DSO level, in order to trade services between the operators and the FSPs with the

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aim of ensuring system global stability, meeting operational constraints and avoiding congestion at either the transmission or the distribution grid. Such an intra-day ancillary services market should be able to handle requests for services by the grid operators (TSO and DSO) for specific time intervals and match them to the respective FSPs' ancillary services offers. The market settlement in the intra-day ancillary services can either rely on financial contracts (performing the market settlement in a continuous approach) or can be based on a market clearing mechanism (ensuring the market settlement and updates participants every few hours, e.g., every three hours using 1-hour time intervals).

It should be clarified that the Intra-Day Energy market is assumed as an existing market and thus no modification have been considered within the Cyprus demo for this market. On the other hand, for the intra-day ancillary services market, the Cyprus demo introduces a new market approach. In the new market approach, an Intra-Day TSO Frequency Reserve Capacity (FCR) market has been defined as the TSO ancillary services market, which relies on a clearing mechanism to settle the provision of fast frequency response (FFR) by FSPs to ensure system satiability. This market receives the demand bids for FCR by the TSO and the generation offers for FFR ancillary services by the FSPs. The large-scale FSPs can directly place their offers in the Intra-Day TSO FCR market, while the small-/medium FSPs should place their offers in the Intra-Day Local DSO Ancillary Services market, which forwards the offers to the TSO ancillary services market along with the prequalification limits concerning the grid capacity for ancillary services (Section 4.4.2), which ensures that the activation of these services cannot overload the local distribution grid.

5.1.1.3 Near real time market

Lastly, the third phase of the market addresses real-time power grid needs. In this near real time market process, the energy balancing aspects are handled by the Global TSO market, usually based on a clearing mechanism an hour ahead of the time window of the actual operation. The Near Real Time TSO Balancing Energy market is usually an existing market, and thus no changes have been introduced by the Cyprus demo.

On the other hand, there is not an established framework for a near real time local DSO market for ancillary services, to manage congestion within the distribution grids. Therefore, the Cyprus demo of the OneNet project emphasizes on this market level to create a new market framework that allows medium- and small-scale FSPs to actively, coordinated by the DSO, provide different services for relieving local congestion and increasing the hosting capacity for RES. Hence, the new market scheme (Near Real Time Local DSO Ancillary Services market) proposed by the Cyprus demo is operated by the Local DSO market which is responsible for the market settlement based on a social welfare maximization clearing mechanism and provides participants with updates on an hourly basis. In this market, the DSO assesses the local grid support needs and places, in an hourly basis, its ancillary services demand bids per substation (either HV/MV or MV/LV) for various services, such as: active power flexibility (ΔP), reactive power flexibility (ΔQ) and phase balancing (PB). On the other hand, the FSPs that

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placed their ΔP, ΔQ, and PB generation offer availability every three hours in the Intra-Day Local DSO Ancillary Services market, which assesses and forwards the offers to the Near Real Time Local DSO Ancillary Services market in an hourly basis. After the settlement of the Near Real Time Local DSO Ancillary Services market, all entities (DSO and FSPs) are informed about the cleared ancillary services (availability services) in order to proceed to the effective coordination of the distribution grid in real time operation, according to the coordination tools developed in Section 4.4.4.

5.1.2 New **ancillary services market schemes of the Cyprus demo**

As stated in the previous subsection and in Figure 18, the day-ahead, intra-day and near real time energy markets are assumed as existing markets and no modifications have been proposed by the Cyprus demo. However, since the ancillary services market schemes are not well established yet in most of the countries and do not exist at all in Cyprus, the Cyprus demo emphasizes on developing new ancillary services market schemes that can potentially improve the operational capabilities of the system operators to ensure the system integrity and stability, while maximizing the hosting capacity for RES through the active involvement of FSPs. The three new market schemes for ancillary services are shown in Figure 18. This figure provides a brief illustration about the interaction between the three Ancillary Services (AS) markets and the process by which the Intra-Day and Near Real Time clearing is served. More information about the three new markets is provided below.

5.1.2.1 Intra-Day Local DSO Ancillary Services Market (ID-DSO-AS)

At this level, the submission takes place for the offered services by the FSPs connected downward the local substation level. FSPs at this level have the capability to contribute to both the transmission and distribution grid needs. For this reason, the FSPs' submissions encompass ancillary services relevant to the Intra-Day TSO FCR market (i.e., active power FFR under frequency disturbances) and to the Near Real Time Local DSO Ancillary Services market (i.e., ΔP, ΔQ, and PB). Through the OneNet system, FSPs submit their offered services for the next 3-hour interval. This submission will be utilized by both the Intra-Day TSO FCR clearing, which occurs every 3 hours, and the Near Real Time Load DSO ancillary services clearing, conducted hourly. Each participant has the flexibility to present their own offer up to 15 minutes before the start of the 3-hour period for which they are willing to provide their services.

Furthermore, at this market level, the calculation of the pre-qualification limits regarding the available capacity for ancillary services at each substation is calculated by the operators according to the pre-qualification tool (developed in Section 4.4.2). These prequalification limits are forwarded (through the OneNet system) by the Intra-Day Local DSO Ancillary Services market to the Intra-Day TSO FCR market. The pre-qualification limits are needed to ensure that the market clearing process cannot cause any overloading conditions at any power substation.

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5.1.2.2 Intra-Day TSO FCR Market (ID-TSO-FCR)

At this stage, an Intra-Day clearing occurs for services that will support the transmission grid stability by ensuring the Frequency Containment Reserve (FCR). Offers for generation of services (availability volume and price) are forwarded from the ID-DSO-AS market, involving FSPs connected at the distribution grid. In addition, generation offers can be directly submitted by FSPs participating solely at the transmission level. At the same time, the TSO defines the required FCR needs (total MW/Hz) to ensure system frequency stability and submit this quantity (as the demand bid with a corresponding price) to the market. These values are communicated through the OneNet system, from which the market operator, the Global TSO Market, retrieves them along with the pre-qualification limits by the operators and performs the market clearing and settlement.

The market operator has a 10-minute time frame, starting 15 minutes before the period to be cleared. Once this time frame elapses, which is at least 5 minutes prior to the clearing period's opening, the market operator returns the market results to participants through the OneNet system.

5.1.2.3 Near Real Time Local DSO Ancillary Services Market (NRT-DSO-AS)

This NRT-DSO-AS market scheme handles Near Real Time (NRT) clearing for services dedicated to supporting the local grid (at each substation level) for congestion management. This market scheme involves Ancillary Services (AS), such as active power upward and downward flexibility (ΔP), reactive power upward and downward flexibility (ΔQ), and phase balancing (PB) for compensate phase asymmetries related to the negative and zero sequence power components of the loading conditions. Generation offers are placed in the ID-DSO-AS market by FSPs connected at the distribution grids. For each clearing scenario, only the FSPs directly associated with the distribution substation (connected downward the specific substation) that requires congestion management services are considered. This specifically pertains to FSPs directly linked to the specific substations.

Simultaneously, the DSO calculates the needs for ancillary services, on an individual substation basis, to ensure that it will be possible to handle expected overloading conditions. The DSO calculates the requirements (demand bids) for active power deviation (ΔP) and reactive power deviation (ΔQ) to ensure the operational limits of each substation are maintained. Additionally, if there are FSPs with capability for asymmetric current injection and if the loading conditions at that specific distribution grid suffer from intense asymmetries, then the DSO can allocate a percentage of phase balancing (PB) services to symmetrize the loading conditions among the three phases, allowing for a more effective utilization of existing grid capacity for congestion management methods. These calculated demand bids values for ancillary services are transmitted from the DSO to the NRT-DSO-AS market through the OneNet system. The operator of the local market, known as the Local DSO Market, retrieves this data and carries out market clearing for each substation separately.

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The NRT-DSO-AS market is clearing on an hourly basis. Similar to the previous phase, the Local DSO Market operator has a 10-minute timeframe, starting 15 minutes before the clearing period. This window allows for the necessary preparations. The operator's actions must conclude at least 5 minutes before the clearing period begins. After this elapsed timeframe, the Local DSO Market operator communicates the market results back to the participants (DSO, FSPs) through the OneNet system.

5.2 Market clearing mechanism

Three new market schemes have been introduced by the Cyprus demo. The ID-DSO-AS market is mainly responsible to pre-asses, and forward bids to the other two markets (ID-TSO-FCR and NRT-DSO-AS), while the two latter markets are responsible for the market settlement and thus, a clearing mechanism is needed. In this section the clearing algorithm for the ID-TSO-FCR and NRT-DSO-AS markets is described.

Both the ID-TSO-FCR and the NRT-DSO-AS markets are utilizing a similar clearing algorithm (with some slight modifications) in order to settle the market. The operation of the market clearing algorithm aims to maximize Social Welfare (SW) while considering all technical constraints involving producers, consumers, and the grid, maintaining a balance in the production-consumption equilibrium [31]-[32]. To achieve the maximization of SW, the following optimization objective function is utilized, as given by (1).

$$\underset{p_g^G, p_d^D}{Maximize} \; SW = \sum_d U_d \, p_d^D - \sum_g C_g \, p_g^G \tag{1}$$

The optimization problem formulation is subjected to the following constraints, given by (2).

$$\begin{aligned} 0 \leq p_d^D \leq \overline{P}_d^D \quad & \forall d \\ 0 \leq p_g^G \leq \overline{P}_g^G \quad & \forall g \\ \sum_d p_d^D - \sum_g p_g^G = 0 \quad & : \lambda \end{aligned} \tag{2}$$

Where, U_d represents bid price of services' demand *d*, C_g corresponds to the offer price of services' generator *g*, $\overline{P}_d^D$ is the maximum services required by the demand *d*, and $\overline{P}_g^G$ represents the capacity of services that can be generated by the FSP *g*.

Based on the above optimization formulation, the algorithm seeks to activate services generation offering units (FSP) with the lowest cost while activating services demand units (TSO or DSO) in a prioritized manner, starting from the one with the highest bid price and progressing towards the cheaper ones. It should be clarified that the clearing optimization algorithm (1)-(2) is formulated in its general form, however in practice, only demand units exist in each market (either the TSO or the DSO) requesting for services to manage the grid. Key

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constraints, as indicated in (2), include the maximum services generation capacity by each FSP and the maximum demand capacity by the operators, and the demand-generation balance of services.

The clearing optimization algorithm, exactly as stated in (1)-(2), is applied to settle the NRT-DSO-AS market. However, for settling the ID-TSO-FCR market an additional constraint is introduced in the clearing formulation (1)-(2), which is related to the pre-qualification limits (Section 4.4.2) for the maximum ancillary services capacity to be assigned to FSPs connected under a specific substation, without overloading the substation.

5.3 Implementation

For the implementation of the new market for the Cyprus demo, corresponding software and Graphical User Interfaces (GUIs) have been designed and developed as tools for each participating entity. These tools have been implemented using MATLAB's App Designer, which provides a user-friendly environment for graphical and visual design, while supporting the execution of the necessary processing and clearing algorithms and facilitating the data exchange between the different market participants. Each tool operates independently, using its own folders to store the data generated by the user and also to store the data received from other participants in the market. This ensures fast and reliable access to all the necessary data by each user.

At the same time, along with storing data in local folders on each user's workstation, each market entity tool communicates with the OneNet system, which acts as an interconnector between entities, to upload/download the relevant data required by each market entity software. To upload/download data to/from the OneNet system, APIs developed by the OneNet project are integrated within the developed tools for each market entity to enable a standardized and seamless interaction between the different users.

In the following sub-sections, all the tools (software/GUIs) developed for each market entity to facilitate all the required functionalities needed by the Cyprus demo market framework are presented.

5.3.1 Producer, FSP, and Retailer Market Participation Tool for Day-Ahead Energy

The developed tool (and the corresponding GUI) for the market participation of producer and FSP in the Day-Ahead Energy market is presented in Figure 19(a). Through this tool, an energy generator (producer or FSP) can participate in the Day-Ahead auction, offering the ability to provide energy per hour, considering an entire day (day ahead). As shown in Figure 19(a), the user has a unique producer name/ID which automatically indicates at which substation it is connected and through the GUI the user can select the specific date, where the generation offers will be placed. Then, the producer or FSP can fill the corresponding fields for the generation capacity and the generation price that corresponds to the generation offers for the day-ahead market, considering an hourly

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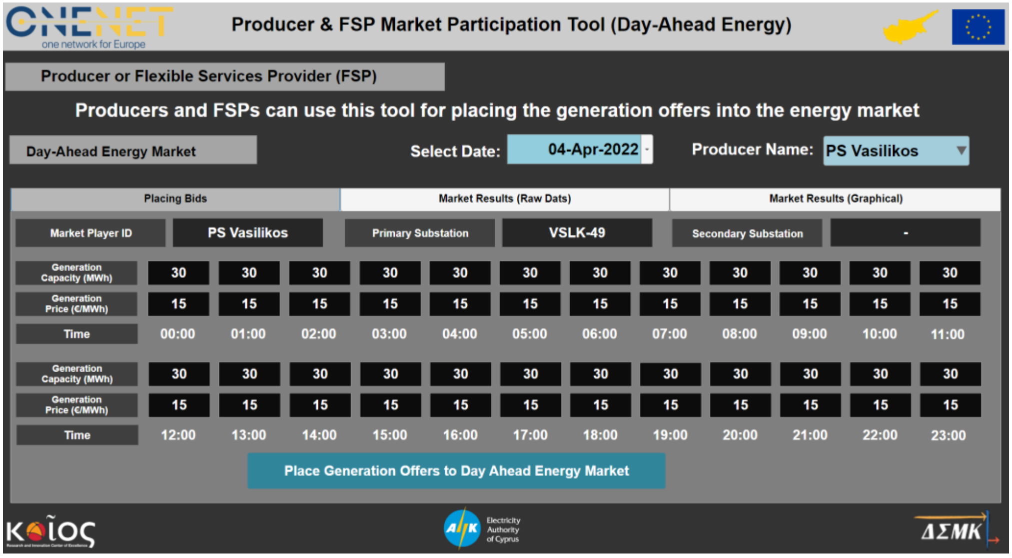
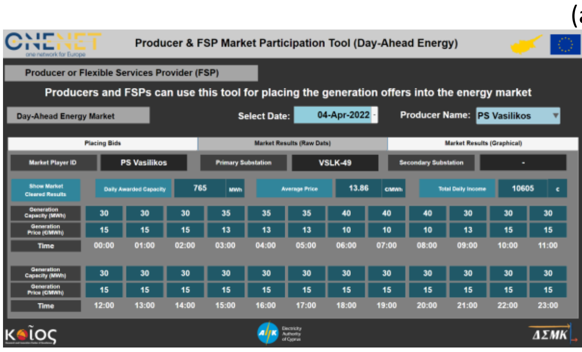
basis. It is noted that a user can only submit offers for their specific Market Player IDs and access to these tools is managed through role-based credentials. Once the user has completed all the fields, the user can click on the "Place Generation Offers to Day Ahead Energy Market" button, which automatically exports their offer into a file, which is stored locally on the user's computer, and simultaneously uploads the generation offers to the OneNet System through an API. The user can review and revise their offers as long as the submission deadline, defined by the market regulation, has not passed.



(a)


(b)

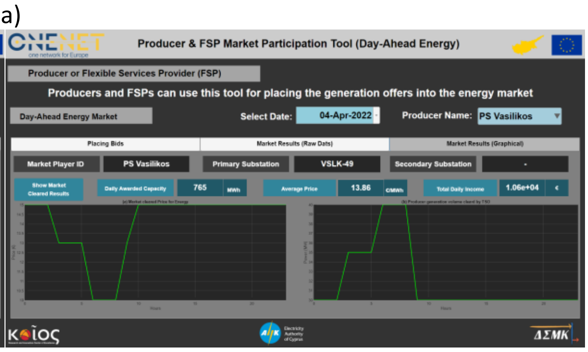

(c)

Figure 19: A developed tool that facilitates producers and FSPs to participate in the day-ahead energy market: (a) Interface to place offers (b) Interface to monitor the market results (as raw data), (c) Interface to monitor market results (visual approach).

Within the same tool, the user can also select the tab "Market Results (Raw Data)", as demonstrated in Figure 19(b), and the "Market Results (Graphical)" tab, as presented in Figure 19(c), to view the market results, after the market settled (cleared). Though these interfaces Figure 19(a)-(b), the users observe the amount of energy awarded to them and the average price for the entire day. The user can also see the awarded volume and the corresponding price for each hourly time interval for the day ahead.

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A similar tool has been created for Retailers as well, where similar functionalities and user interface format has been considered, as shown in Figure 20. Through this tool, the Retailers participating in the Day-Ahead market can declare their energy consumption needs (demand capacity) and the price they are willing to pay (demand bid price) for the specific energy. The main differences between the tools of Figure 19 and Figure 20, are that the producers (FSPs) has changed to Retailers, the generation capacity to demand capacity, and the generation price to demand bid price, while the tools functionalities remain similar between the two tools. Hence the tool of Figure 20 facilitates the market participation of retailers to the day-ahead energy market.

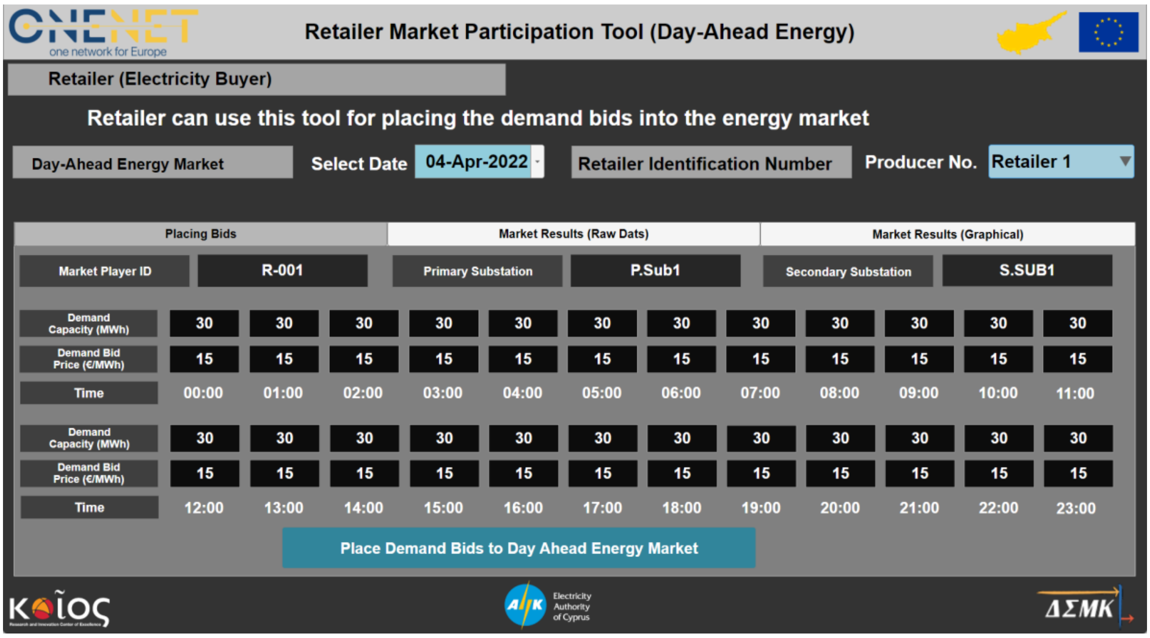
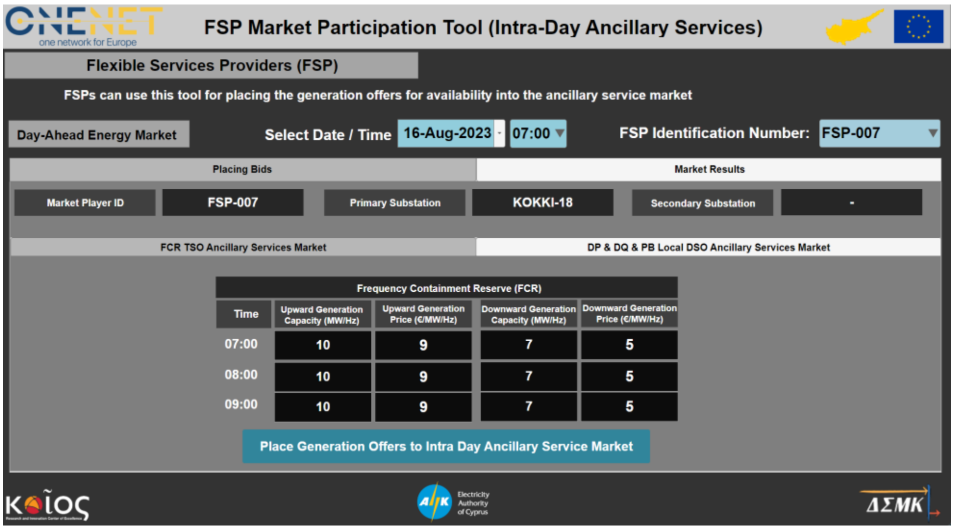
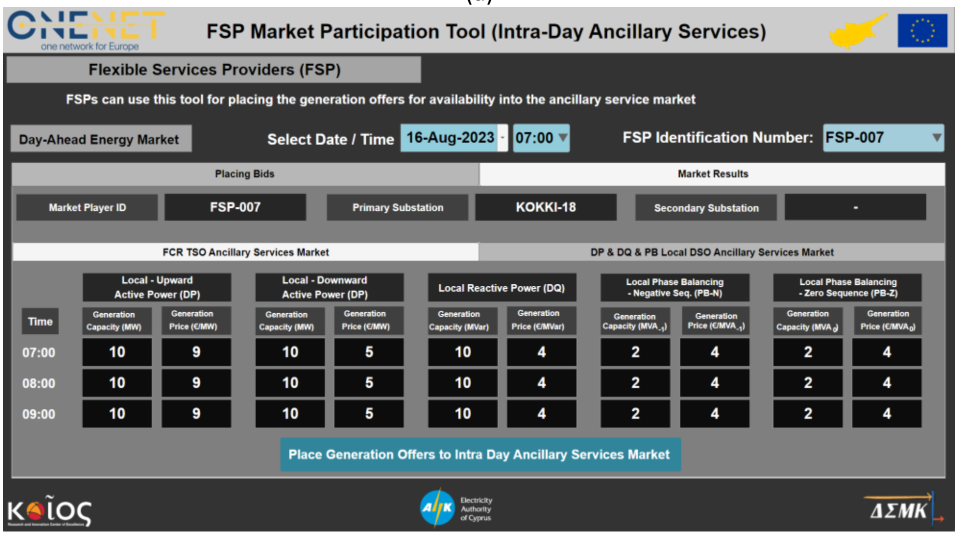


Figure 20: A developed tool that facilitates retailers' participation in the day-ahead energy market.

5.3.2 FSP Market Participation Tool for Intra-Day Ancillary Services



(a)



(b)

Figure 21: A developed tool facilitating FSPs to participate in the intra-day ancillary services market: (a) to provide FFR to be forwarded to the ID-TSO-FCR market, and (b) to provide ΔP, ΔQ, and PB services that will be forwarded to the NRT-DSO-AS market.

An additional tool has been developed to enable the FSP participation in the ID-DSO-AS market, as show in Figure 21. Similar to the previous tool, the FSP should select its market participation ID (which is connected to a specific substation) and the corresponding date/time where the FSP would like to place its generation offer. Then, the user can select either the "FCR TSO Ancillary Services Market" tab as shown in Figure 21(a), or the "DP & DQ & PB Local DSO Ancillary Services Market" tab as illustrated in Figure 21(b), to submit the FSP offers to provide the corresponding ancillary services to each market scheme by filling the generation capacity and price

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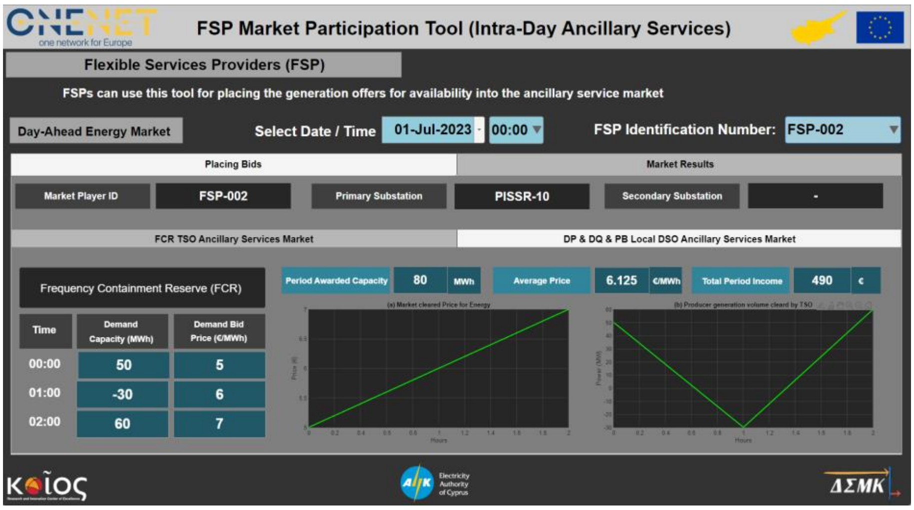
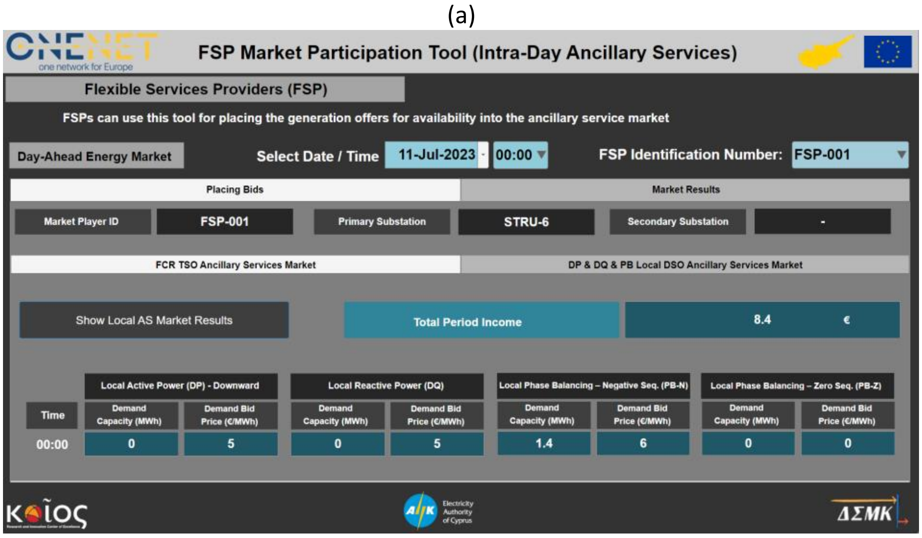
for each service, considering a 3-hour timeframe with 1-hour resolution. The generation offers are submitted (stored locally and sent to the market through the OneNet system) as soon as the user clicks on the "Place Generation Offers to Intra Day Ancillary Services Market" button.

The same tool can also be used to observe the market results after the ID-TSO-AS or NRT-DSO-AS markets are settled/cleared. Examples of the interfaces showing the market results are demonstrated in Figure 22 for the two ancillary services markets.



(a)



(b)

Figure 22: A developed tool facilitating FSPs to monitor the market clearing results: (a) the FSP can observe the clearing results of the ID-TSO-AS market, and (b) the FSP can monitor the NRT-DSO-AS market results.

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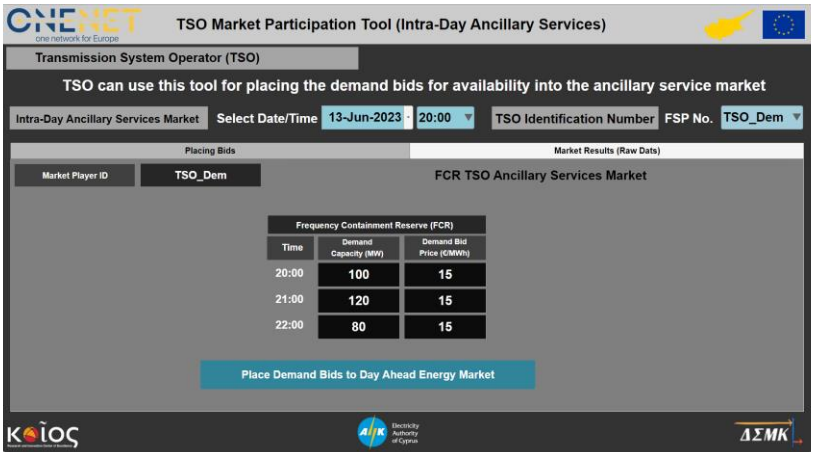

Figure 23: A developed tool for TSO to place the FCR demand bids to the ID-TSO-AS market.

5.3.3 TSO Market Participation Tool for Intra-Day Ancillary Services

A similar market participation tool has been developed for the TSO as well, as presented in Figure 23. Through the “Placing Bids” tab of this tool, the TSO can place the demand bids for FCR, mandated for the grid stability, to the ID-TSO-AS market. The demand bids for FCR (MW/Hz) are placed in an hourly basis for a selected 3-hour period of the intra-day market. After the ID-TSO-AS market is cleared, the TSO can use the same tool to monitor the market results, through the “Market Results (Raw Data)” tab.

5.3.4 DSO Market Participation Tool for Intra-Ahead Ancillary Services

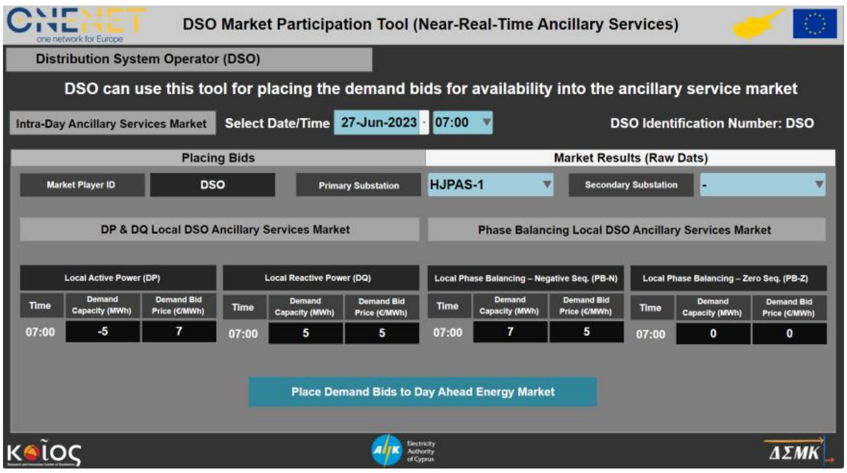

Figure 24: DSO market participation tool for placing demand bids for AS in the NRT-DSO-AS market.

A DSO market participation tool has also been developed for enabling the DSO market participation in the NRT-DSO-AS market, as it is illustrated in Figure 24. In this tool, the DSO can navigate to the “Placing Bids” tab

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to place the demand bids (volume and price) for Δ*P*, Δ*Q* and PB services for the selected primary or secondary substation, by filling the corresponding fields and clicking the "Place demand bids" button.

After the NRT-DSO-AS market clearing, the DSO can also navigate in the "Market Results (Raw Data)" tab to observe the market results.

5.3.5 Global TSO Market Clearing Tool

The clearing process for the Day-Ahead and Intra-Day markets is overseen by the TSO market operator using the "Global TSO Market Tool", as demonstrated in Figure 29. This tool has been developed to enable the market operator to independently execute the day-ahead energy market clearing ("Day-Ahead Energy Market") and the intra-day clearing for ancillary services ("Intra-Day Ancillary Services Market"). The four-step clearing process for settling the ID-TSO-AS market is described in this subsection, considering the following steps: (a) loading the AS demand bids as determined by the TSO by pressing the "1. Load Demand Bids" button; (b) loading all the AS offers (for provisioning FCR) placed by the FSPs by pressing the "2. Load Generation Offers" button; (c) executing the market clearing algorithm by pressing the "3. Clear Market" button; and (d) communicating the results to all the market participants by pressing the "4. Send Market Results" button.

Figure 25: DSO market participation tool for placing demand bids for AS in the NRT-DSO-AS market.

After the market settlement, the market operator can view market clearing results through a numerical and graphical format, as well as to examine how the results were distributed among the energy market participants, by navigating to the "Market Results" tab.

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5.3.6 Local DSO Market Clearing Tool

The settlement and clearing process for the NRT-DSO-AS is performed by the DSO market operator, by using the developed "Local DSO Market Tool", presented in Figure 26. This tool empowers the market operator to execute the near real time clearing of the local DSO ancillary services market on an hourly basis for each substation individually. The market operator follows a four-step clearing process similar to the previous case described for the Global TSO Market. After selecting the substation for which the market should be settled, the market clearing process includes: (a) loading the AS demand bids as determined by the DSO by pressing the "1. Load Demand Bids" button; (b) loading all the AS offers placed by the FSPs by pressing the "2. Load Generation Offers" button; (c) executing the market clearing algorithm by pressing the "3. Clear Market" button; and (d) communicating the results to all the market participants by pressing the "4. Send Market Results" button.

The market operator can review the market results after the market clearing process is completed as well, by navigating to the "Market Results" tab.

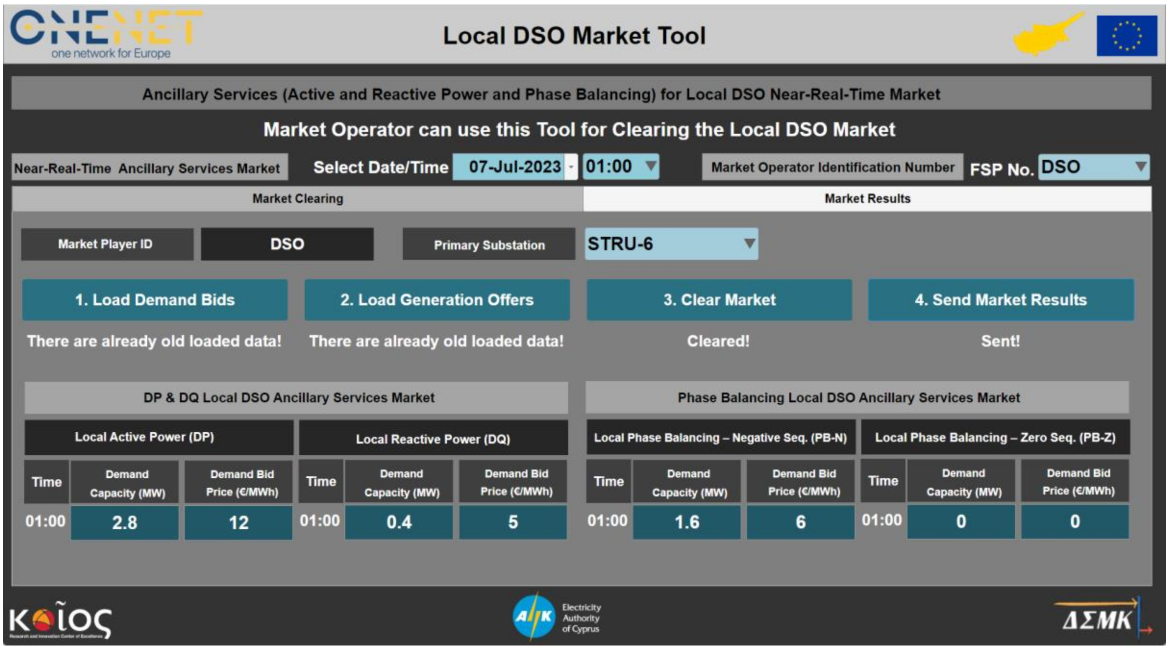

Figure 26: Local DSO Market tool to manage and clear the NRT-DSO-AS market.

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6 Cyprus Demo Integration through the OneNet system

6.1 Information exchange through the OneNet System

The ABCM-T platform provides the necessary tools for operators to monitor and manage the transmission grid while considering effective collaboration with other entities, including the market, DSO, FSPs, and end-users. On the other hand, the ABCM-D platform equips the DSO with valuable tools for real-time monitoring and coordination of FSPs within the distribution grid to ensure an efficient and effective operation of the distribution grid.

To achieve the primary goal of the OneNet project, which aimed at cost-effective and environmentally friendly operation of the complete electricity infrastructure, effective collaboration was facilitated among the TSO, DSO, market operator, and FSPs through the OneNet system. This was achieved by enabling standardized exchange of data and information among different entities. As a result, all distinct platforms developed for each entity/actor were compatible for data exchange through the OneNet system.

The compatibility of ABCM-T and ABCM-D platforms with the OneNet system for standardized information exchange enabled collaboration and coordinated actions between the different entities (TSO, DSO, market operators, FSPs). The standardized exchange of information between different entities was realized through the API developed for communication between any platform and the OneNet system. It should be note that the OneNet system was developed in WP6 of the OneNet project and was given to all the OneNet demos as docker (OneNet connector) for integration. In this sense, more information about the configuration of the overall configuration, development, and architecture of the OneNet system can be found in [33]. Furthermore, information regarding the information exchange in the Cyprus demo through the OneNet system can be found in Section 6.2 of this deliverable.

The OneNet system coordinated which information would be exchanged between specific entities. Figure 27 depicted the main information exchange between the main entities of the Cyprus demo that is facilitated through the OneNet system. Examples of this information exchange, through the OneNet system, between the different platforms include the procurement of products by the TSO and DSO in the corresponding market, update for the corresponding FSPs in the transmission and distribution level, bids placement to the corresponding market by the FSPs, update of the FSPs regarding the market clearing results, exchange of prequalification limits between the market and the two platforms, as well as exchange of the FSPs evaluation report between the platforms and the FSPs. The integration of the ABCM-T and ABCM-D platforms was achieved by ensuring compatibility with the standardized information exchange process defined by the OneNet system.

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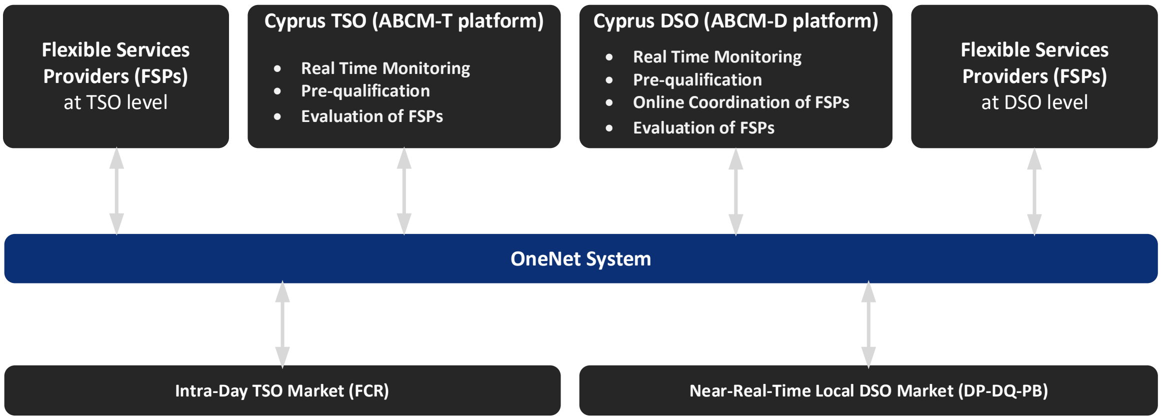

Figure 27: Integration of the ABCM-T and ABCM-D platforms through the OneNet System.

The way and the sequence through which the OneNet system interacts with participants in the electricity market is explained in detail below for the two cases of the spot market: 1) at an intra-day level to support FCR (Frequency Containment Reserve), and 2) in real-time for local active balancing and congestion management.

6.1.1 Scenario for Intra-Day TSO Market clearing (FCR)

For the execution of the Intra-Day market clearing, all the necessary information is provided to the OneNet system for a 3-hour period, at least 15 minutes before the start of that period, by the FSPs connected at both TSO and DSO levels, as well as from the ABCM-T platform. The procedure for the offers and bids placement as well as the market clearing of the Intra-Day FCR market is described in steps below.

Step 1: TSO procures the demand for Frequency Containment Reserve (FCR) and its prequalification limits. Through the ABCM-T platform, the TSO provides information in CSV files, following the format shown *Figure 28* (a). The TSO submits a file to the system with 3 rows, one row for each hour, specifying the energy required to maintain FCR network stability. Each row includes date, time, TSO's ID number, the amount of energy in MW required for that hour (Dem Cap), and the price per MW that the TSO is willing to purchase for this energy (FCR offer price). Additionally, the DSO submits information about the prequalification limits for each substation in CSV format, as shown in *Figure 28*(b). This file contains as many lines as the substations in the network (58 for the Cyprus system). Each line records the date, time, network operator's ID number, substation name, substation number, upper limit, and lower operational limit of the substation in kW. For covering the next three hours, the ABCM-D platform submits 3 separate files regarding the prequalification limits (one for each hour). The files from the TSO procurement as well as the prequalification are submitted to the OneNet system.

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Step 2: FSPs submit the generation for frequency containment reserve (FCR)

After the publication of offers by the TSO, the FSPs provide information in CSV files with the format presented in *Figure 29*. Each FSP submits a file to the system with 3 lines, one line for each hour that contains the date, time, ID number corresponding to the FSP, the main substation number to which the FSP is connected, the

secondary substation number if applicable, the amount of energy in MW that the FSP can provide for FCR and the price per MW (€/MW) at which the FSP sells the corresponding energy. The file with the offers is submitted to the OneNet system to be used by the market clearing algorithm.

TSO

IDAS_TSO_DemBid_FCR_2022-05-09_1500.csv				
Date	Time	TSO Number (TSO-xxx)	FCR Dem Cap	FCR Offer Price
2022-05-09	1500	001	3	50
2022-05-09	1600	001	3	45
2022-05-09	1700	001	2	60

(a)

Prequalification

IDAS_PreQualLimit_09-Jul-2023_0.csv						
Date	Time	Operator ID	Substation Name	Substation Number	Upward Availability	Downward Availability
09-Jul-2023	0:00	DSO	HAJIPASCHALIS	1	715,965	-906,453
09-Jul-2023	0:00	DSO	PAPHOS	2	600,671	-1,050,381
09-Jul-2023	0:00	DSO	AKURSOS	3	281,589	-368,902
09-Jul-2023	0:00	DSO	POLIS	4	18,032	-222,767
⋮	⋮	⋮	⋮	⋮	⋮	⋮

Figure 28: a) TSO demand bid (b) Prequalification limits list

- **FSPs place their generation offers to the market**

IDAS_TSO_GenOffer_FSPxxx_2022-03-21_1500.csv						
Date	Time	FSP Number (FSP-xxx)	Primary Sub.	Secondary Sub.	FCR Gen Cap	FCR Offer Price
2022-03-21	1500	001	34	23	3	50
2022-03-21	1600	001	34	23	3	45
2022-03-21	1700	001	34	23	2	60

Figure 29: FSPs generation capacity for the FCR market

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Step 3: Intra-day TSO Market (FCR) Clearing

After the execution of Steps 1 and 2, which can be executed up to 15 minutes prior to the start of the clearing period, the TSO Market operator is responsible for clearing the bidding process for this period within a maximum 10-minute timeframe. This indicates that the market results will be available at least 5 minutes before the period begins. To achieve this, the operator retrieves information from the OneNet system concerning demand, production, and prequalification limits in CSV format.

Step 4: Updating information to FSPs and TSO from the OneNet system

After the clearing of the market, the market operator submits to the OneNet system updated files with the same format as the one shown in *Figure 28* (a) and *Figure 29* for the TSO and the FSPs, five minutes before the period starts, while the FSPs and the TSO retrieve the cleared results from the OneNet system. Specifically, each FSP receives the same file format they initially submitted (*Figure 29*), with the distinction that the "FCR Gen Cap" column contains the cleared energy quantity that they were assigned to sell for that specific hour (which could be zero in case that the FSP was not qualified according to the market clearing algorithm), while the "FCR Offer Price" column includes the cleared market price for the specific product. Similarly, the TSO obtains the same file format as the one shown in *Figure 28* (a), which should have the same demand capacity as the one initially submitted by the TSO (if the market could satisfy the demand capacity through the offers submitted to the market by the FSPs), along with the market clearing price for that specific hour. Additionally, the TSO has access to all market clearing files related to FSPs, since it is important to know the FSPs that will contribute to the FCR support.

6.1.2 Scenario for NRT Local DSO market clearing (DP-DQ-PB)

For the execution of the near real-time market clearing, all the necessary information is provided to the OneNet system for the entire one-hour period, at least 15 minutes before the start of this period. This information originates from the FSPs connected at the DSO level and from the ABCM-D platform. As in the previous scenario, the communication structure is described by the diagram in Figure 27.

Step 1: The DSO procures the local NRT demand for Ancillary Services support

Through the ABCM-D platform, the DSO provides information in CSV files with the format shown in *Figure 30*. In this figure, the DSO submits a file to the system with a single line for the upcoming hour, containing information about the required energy needed for the following hour in order to overcome congestion of the grid or power quality issues. This line includes details such as the date, time, ID number corresponding to the DSO, primary substation number, secondary substation number if applicable, required energy in MW, cost in €/MW, required reactive power in MVar, cost in €/MVar, required energy in MW for negative sequence balancing, cost in €/MW, required energy in MW for zero sequence balancing, and cost in €/MW. The corresponding file is uploaded to the OneNet system.

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DSO

NRTAS_DSO_DemBid_DSOxxx_date_hour.csv													
Date	Time	DSO Number (DSO-xxx)	Primary Sub.	Secondary Sub.	DP Dem Cap	DP Bid Price	DQ DemCap	DQ Bid Price	PB-N Dem Capac	PB-N Bid Price	PB-Z DemCap	PB-Z Bid Price
2022-03-21	h	001	34	23	3	50	3	50	3	50	3	50

Figure 30: DSO demand bid for NRT market

Step 2: FSPs procure the generation for local NRT Ancillary Services support

Simultaneously with the submission of the bids from the DSO through the ABCM-D platform, the FSPs located at the local substation level and willing to participate in the local grid support through the market also provide offers for the different products. The FSPs provide information in .csv files with the format shown in Figure 31. Each FSP submits a file to the system consisting of 3 lines, one line for each hour for which they intend to bid. Although the offer is for a 3-hour period, the market clearing is performed every hour. Hence, the offer submitted by the FSP will be used for 3 consecutive clearing periods. Each line includes details such as the date, time, ID number corresponding to the FSP, primary substation number to which the FSP is connected, secondary substation number if applicable, generation capacity for active power in MW, cost in €/MW, generation capacity for reactive power in MVar, cost in €/MVar, generation capacity for energy in MW for negative sequence balancing, cost in €/MW, generation capacity in MW for zero sequence balancing, and cost in €/MW. The corresponding file is uploaded to the OneNet system.

FSPs

IDAS_DSO_GenOffer_FSP-004_03-Jul-2023_0h.csv												
Date	Time	Producer ID	Primary Substation	Secondary Substation	Local DP Gen Capacity	DP Offer Price	Local DQ Gen Capacity	DQ Offer Price	Local PB-N Gen Capacity	PB-N Offer Price	Local PB-Z Gen Capacity	PB-Z Offer Price
03-Jul-2023	0:00	FSP-004	23	32	11	8	11	5	3	4	3	4
03-Jul-2023	1:00	FSP-004	23	32	10	8	10	5	2	4	2	4
03-Jul-2023	2:00	FSP-004	23	32	5	9	10	5	2	4	2	4

Figure 31: FSP generation capacity for the NRT market

Step 3: NRT Local DSO Market Clearing (DP-DQ-PB)

After the execution of Steps 1 and 2, which should be concluded 15 minutes before the start of the clearing period, the DSO Market operator is responsible for the market clearing within a maximum time window of 10 minutes. This implies that the market results will be available at least 5 minutes before the period starts. To achieve this, the operator retrieves the CSV files uploaded by the DSO and the FSPs through the OneNet system regarding the demand and generation.

Step 4: Updating information to FSPs and DSO from the OneNet system

The FSPs and the DSO retrieve the market clearing results from the OneNet system 5 minutes before the period starts. Specifically, each FSP receives the market clearing for each hour in the form of a file, as shown in Figure 32. The difference from the file submitted by each specific FSP is that it contains information for only one hour

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(one row), while columns DP, DQ, PB-N, PB-Z, the awarded energy quantity to the FSP (according to the market clearing algorithm) for that specific hour is indicated (it can be zero in case the FSP was not qualified). The cleared price columns (e.g., DP cleared price) show the clearing price that was cleared for all market participants for each product. Similarly, the DSO receives the same file format as the one shown in *Figure 30*, which is expected to have the same demand value (for each product) as initially stated by the DSO (this is the case when the market was able to meet the DSO bids through FSP offers with cheaper energy than the DSO's offer), along with the market clearing price for that hour (for each product). Additionally, the DSO has access to all market clearing files of the FSPs, in order to know which FSPs will participate to the NRT Local DSO network support for the next three hours.

DSO market results send to an FSP

IDAS_DSO_MarketClear_FSP001_2022-03-21_1500.csv												
Date	Time	FSP Number (FSP-xxx)	Primary Sub.	Secondary Sub.	DP AwarGen Capac	DP Cleared Price	DQ AwarGen Capac	DQ Cleared Price	PB-N AwarGen Capac	PB-N Cleared Price	PB-Z AwarGen Cap	PB-Z Cleared Price
2022-03-21	1500	001	34	23	3	50	3	50	3	50	3	50

Figure 32: NRT market result for FSPs and DSO

6.2 OneNet system integration

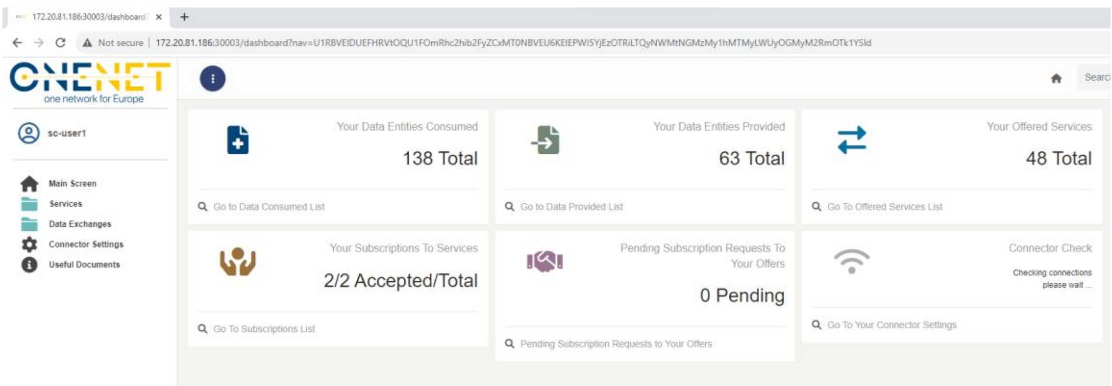

Figure 33: OneNet System Interface – Main page

The OneNet system supports the communication among participants in the Cyprus demo, serving as an intermediate medium for communication and data exchange. The system is utilized at two levels by the participants in the market. The first level is the User Interface (UI) Application (Figure 33), where each participant connects using their personal account (username and password) and states the conditions under which he will use the OneNet system, either for provision of data to others or for gathering data. The second level involves the API that enables users to communicate with the system through programming languages. At this level, the Graphical User Interfaces (GUIs) developed for each participant in the electricity market are involved. Based on

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the conditions set by the first level of communication, data exchange occurs for offers, demands, and final market results.

The integration of the market system was achieved by installing the Docker platform, which supports its functionalities, on the local server of the University of Cyprus. Subsequently, by utilizing the UI Application, under the Connector settings (Figure 34), the system was configured to establish communication with users both within and outside the University of Cyprus. This provides flexibility for every user of the electricity market system to interact in real-time with the rest of the system.

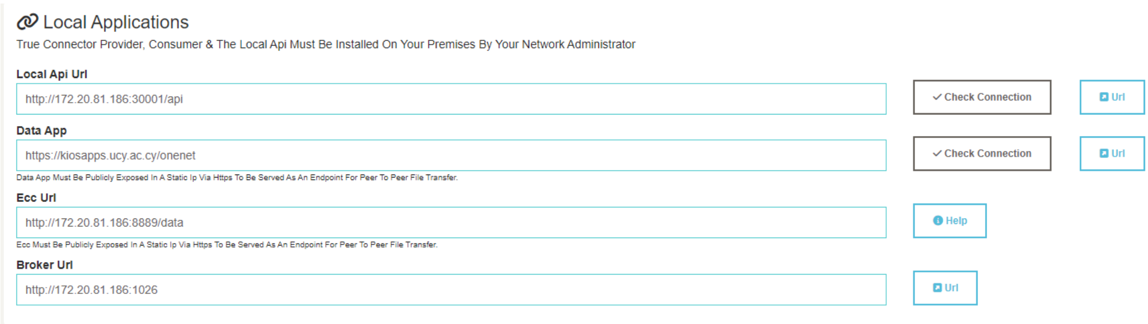

Figure 34: OneNet System Interface – Connector Setting

Below, the procedure for configuring a condition using the UI Application of the OneNet system assuming that user (A) provides data to another user (B) is described.

Step 1: User A, logged into its system account, selects "Services" and then "My Offered Services". By clicking "+New," User A has the option to create a new condition, giving it a title like "Offers for FCR Market" and choose the appropriate category, such as "Business Object," which pertains to the condition's context, like market results or prediction data, etc. Additional details such as the time period, sample uploads, supported file formats, and a description can also be added to the condition. Once the creation is complete, the user saves the condition.

Step 2: User B, after logging into its own account, goes to "Services" and chooses "My Subscriptions." Under the "Select Offering" section, they can locate the condition titled " Offers for FCR Market " and request participation. User B can also add comments to this request, to be sent to User A, the creator of the condition.

Step 3: After the request from User B is submitted to the system, User A can review it under "Services" > "Requests" and can either accept or reject it. If the request was accepted, this means direct activation of a communication channel between User A and User B.

Step 4: After the acceptance of the request submitted by User B, User A can navigate to "Data Exchanges" → "Provide data" and upload a file named for instance "Offers for 13:00". User A should assign a title like "Transfer Offers for FCR Market " and select the condition "Offers for FCR Market" from the "Data Offering" field. Additional comments can be added for those who will use the file.

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Step 5: User B, under "Data Exchanges" → "Consume Data," can find the new file, titled "Transfer Offers for FCR Market" and select the transfer to download the file "Offer for 13:00" to its computer. This completes the cycle of data transfer between two participants in the OneNet system.

Based on the description above, a distinct condition is necessary for each information exchange path between participants. For instance, in the scenario of an executed market, the diagram in Figure 35 illustrates communication paths between all participants. For FSP1 to communicate with the Local DSO Market administrator, at least two conditions are required. One condition is created by FSP1 and involves the participation of the Local DSO Market to this condition, since the FSP1 will send the offers to the Local DSO Market, while the Local DSO Market will execute the market clearing based on the offers sent by all the FSPs. The other condition is created by the Local DSO Market and involves the participation of FSP1, since the Local DSO market will send the market clearing results to FSP1 and FSP1 will retrieve the results through the OneNet system.

It should be noted that if an FSP (Flexibility Service Provider) wants to participate in both the DSO and TSO markets, they must establish separate conditions for each market. Similarly, they need to participate in two different conditions (one with the DSO market and one with the TSO market) to receive results. Accordingly, the system administrators (TSO and DSO) should also have a condition for the market that they are going to submit their demands. Additionally, they also need to engage in a condition with the market operator to receive the corresponding market results.

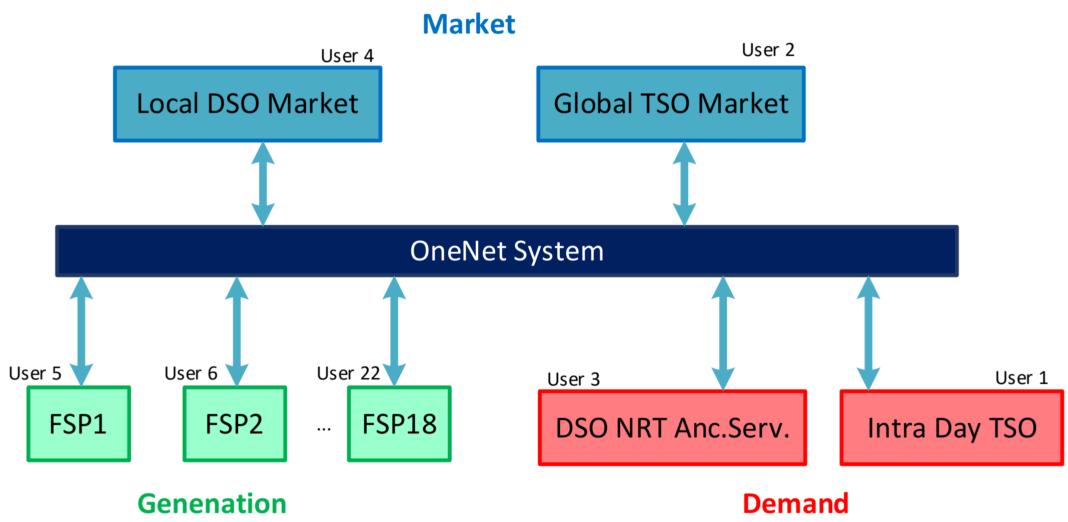

Figure 35: Communication paths between OneNet System and Market participants

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7 Demo integration with an actual residential prosumer

Another important activity of the Cyprus Demo was the integration of an actual residential prosumer in the whole demonstration process. This was achieved through the OneNet Open Call procedure, which enables the involvement of a third-party company, H. Wise Wire Energy Solution Limited (WiseWire), to facilitate the integration of an actual prosumer (through the OneNet – ActiveProsumer project), enhancing this way the engagement of household consumers towards the cost-effective operation of power grids. The main activities regarding the development of the communication framework and the prosumer's local energy management to enable the active involvement of the actual prosumer in the grid management process can be found in [x], along with some key results. It is noted that this section is only emphasizing on the activities that took place to enable the proper integration of the prosumer in the digital twin and its real-time coordination by the ABCM-D platform to relieve grid congestion.

7.1 Integration approaches

The key objective of the OneNet - Active Prosumer project was to enable the participation of actual prosumers in distribution grid management, allowing the provision of flexibility services to the grid. Towards this direction, a lightweight and secure communication framework is developed by WiseWire to facilitate the fast and reliable communication between prosumers and the DSO, while an actual prosumer (operated by WiseWire) was made available to participate in the Cyprus demonstration.

The involvement of the actual prosumer is achieved by considering the two following approaches:

(a) **Approach 1 - Integration:** The prosumers is providing real-time field data regarding its operation (i.e., grid power exchange, photovoltaic generation, load consumption, battery operation and charging status) every 30 seconds, allowing the replication of the prosumer operation within the digital twin of the Cyprus power system. With this "read-only" approach, real data for the operation of an actual prosumer are integrated in the Cyprus demonstration to involve real live data from an actual household consumer.

(b) **Approach 2 – Coordination:** The second approach is an extension of the first approach, where both "read and write" capabilities are considered to ensure the active involvement of an actual consumer. After the integration of the prosumer in the real-time digital twin environment (as described in Approach 1), the ABCM-D platform was able to observe both the grid and prosumer operating conditions for monitoring and coordination purposes. Measurements received by the digital twin facilitates the real-time monitoring of the distribution grid (Section 4.4.1), and then, the Distribution Grid Coordination tool (Section 4.4.4) is generating coordination signals for managing FSPs and prosumers operation to relieve congestion, considering the availability of FSPs and prosumers as cleared by the NRT-DSO-AS market. The coordination signals (ΔP^* and ΔQ^*) by the Distribution Grid Coordination tools are sent to both the digital twin (where other prosumers are virtually modelled) and to the actual prosumer through the lightweight and secure communication framework (WiseWire cloud). The latter coordination signals are received by the actual prosumer's energy management system that internally manages flexible resources in order to track the DSO coordination set-points (ΔP^* and ΔQ^*). The regulated response of the actual prosumer is then communicated back to the digital twin of the Cyprus power grid, to close the loop and effectively manage the distribution grid congestion.

The overall architecture to facilitate both approaches for involving an actual prosumer in the Cyprus demo is demonstrated in Figure 36.

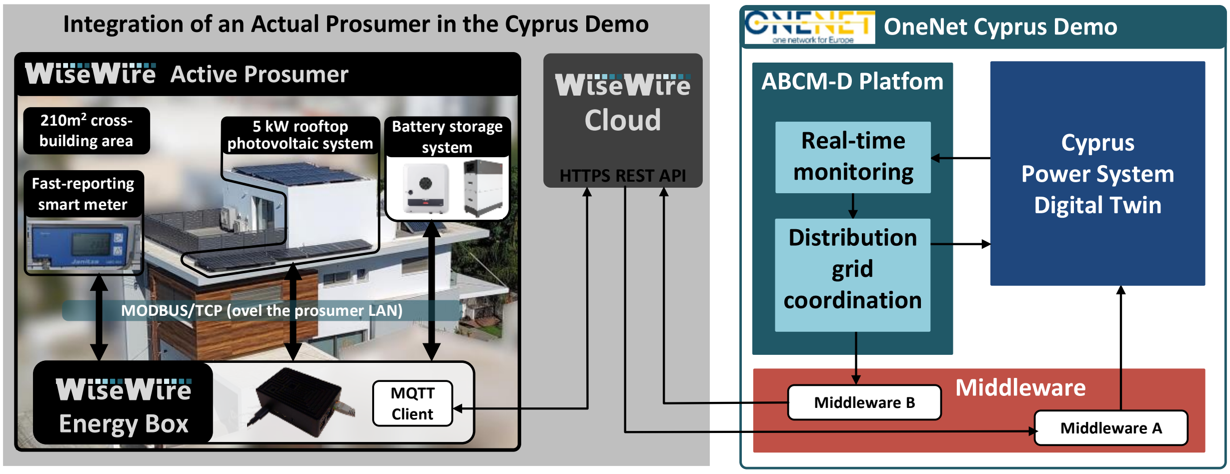

Figure 36: Overall architecture for involving an actual prosumer in the Cyprus demo, considering both integration and coordination approaches.

7.2 Middleware development to facilitate integration

To facilitate the integration of the actual prosumer in the Cyprus power system digital twin and the real-time coordination of the actual prosumer by the ABCM-D platform, a middleware has been developed to ensure the periodic exchange of data between the two entities (i.e., WiseWire, OneNet Cyprus Demo), as illustrated in Figure 36. This middleware is responsible to exchange data in a timely and secure manner between the WiseWire cloud, the ABCM-D platform and the digital twin of the Cyprus demo. Middleware development is separated into two parts, as described below.

- **Middleware A – Integration:** The first part of the middleware (Middleware A) is responsible for integrating in real time the actual prosumer in the distribution grid's digital twin environment. To achieve this, Middleware A has been developed to act as an interconnector between the actual

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prosumer and the digital twin. On the one side, the middleware establishes an HTTPS REST API communication with the WiseWire cloud system in order to read the last value (updated every 30 seconds) regarding the operating conditions of the actual prosumer (i.e., active and reactive power exchange between the prosumer and the grid, active and reactive power generation by the prosumer's photovoltaic system, active and reactive power operation of the BESS and its state of charge). After receiving the information from the WiseWire cloud, the middleware is responsible to pass this information to the digital twin. This is achieved through a Modbus TCP communication where the prosumer's operating condition are provided as set-points in order to be reproduced in the simulation model of the digital twin. The corresponding values are written by the middleware in a holding register of a Modbus TCP server, implemented within the Real Time Simulator (RTS) where the digital twin is running. As soon as the prosumer's operating conditions are updated in the corresponding holding registers, the simulation model is configured accordingly to replicate those conditions by the models emulating the load, PVs and BESS of the prosumer.

- **Middleware B – Coordination:** After the integration of the prosumer within the distribution grid's digital twin, the ABCM-D platform receives the digital twin's operating condition to facilitate the real-time monitoring and coordination of the distribution grid. In case of contingencies the coordination tool (Section 4.4.4) generates reference signals (ΔP^* and ΔQ^*) to be sent to all the available prosumers or FSPs able to provide active and reactive power flexibility, according to the NRT-DSO-AS market clearing results. The coordination signals for the flexible prosumers or FSPs virtually modelled within the digital twin are sent directly to the digital twin, considering the middleware of the ABCM-D platform, as described in Section 4.3.2. However, the reference signals (ΔP^* and ΔQ^*) for the actual prosumer need to be sent from the ABCM-D platform to the WiseWire prosumer, which is achieved by writing those values in the WiseWire cloud through an HTTPS request based on REST API. Then, the WiseWire cloud is responsible to pass this value to the WiseWire Energy Box located within the actual prosumer, which locally coordinates the prosumer assets to follow the coordination set-points of the DSO.

7.3 Validate the actual prosumer integration

After developing all the necessary activities to integrate the actual prosumer in the digital twin and to enable the live data feeding for the residential prosumer, a validation process has been established to verify that the prosumer operation is timely and precisely replicated in the digital twin.

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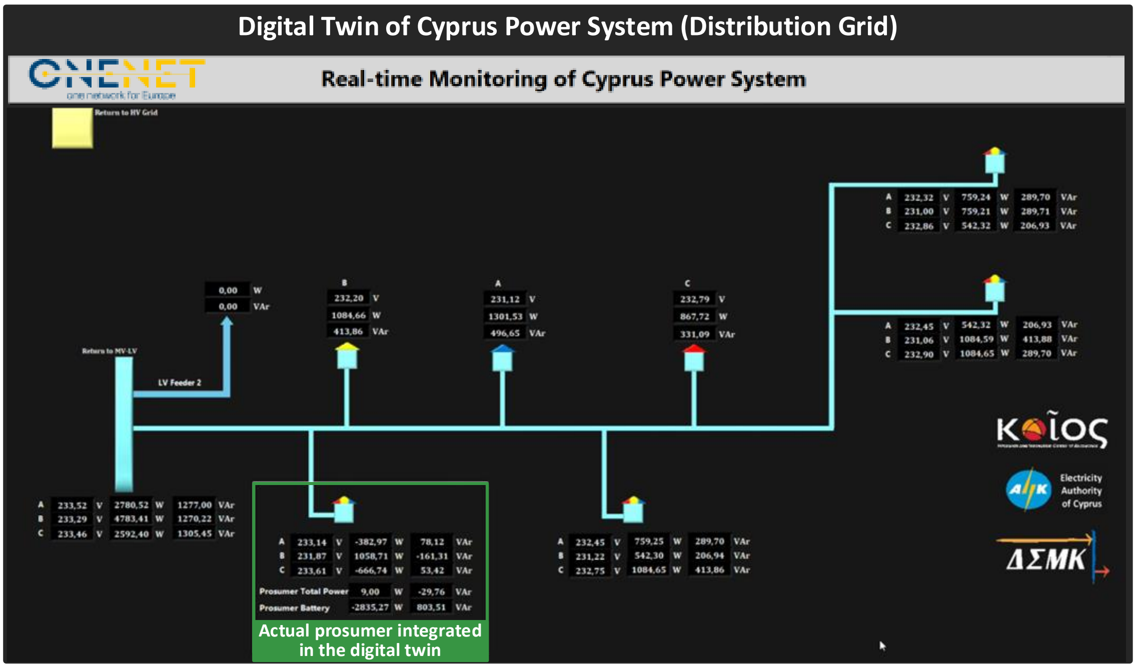
To validate the correct integration of the prosumer in the Cyprus power system's digital twin, we took simultaneous screenshots from the WiseWire Cloud interface and the monitoring interface of the ABCM-D platform. These are presented in Figure 37(a) and Figure 37(b) accordingly, where the prosumer operates in its standard mode with a self-consumption scheme for its battery system. The WiseWire Cloud interface (Figure 37(b)) indicates that the battery discharges at 2.83 kW and injects -0.802 kVAr to balance the prosumer's total power. Meanwhile, according to the ABCM-D platform (Figure 37 (a)), the battery injects 2.835 kW and absorbs 0.803 kVAr. It's important to note the reversed power flow direction assumed on both interfaces. For a detailed breakdown: according to the WiseWire Cloud, the prosumer's total power is 0.021 kW and 0.014 kVAr (a: -0.378 kW, 0.089 kVAr; b: 1.060 kW, -0.132 kVAr; c: -0.660 kW, 0.056 kVAr). In contrast, the ABCM-D platform reports 0.009 kW and 0.029 kVAr (a: -0.382 kW, 0.078 kVAr; b: 1.058 kW, -0.161 kVAr; c: -0.666 kW, 0.053 kVAr).

(a)



(b)

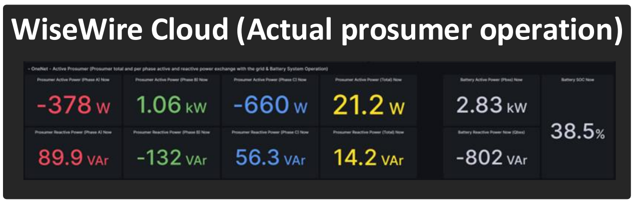


Figure 37: Validation of the precise integration of the actual prosumer in the Cyprus demo digital twin. (a) Monitoring of the distribution grid's digital twin operation through the ABCM-D platform where the actual prosumer is replicated as well, (b) Monitoring of the actual prosumer operation according to the WiseWire cloud interface for the corresponding instant.

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Ultimately, the prosumer's total active and reactive power are near zero. This is because, in this scenario, the battery offers self-consumption services, minimizing the power exchanged with the grid.

The minor discrepancies between the actual prosumer's operation and its digital twin, on the order of ±50 W or ±50 VAr, are acceptable since the replicating accuracy is achieved with less than 1% error. The discrepancies exist, because measurements from the actual prosumer serve as reference set-points for dynamic load blocks and detailed battery storage system models. Consequently, some noise in the digital twin's measurements is anticipated. Through the results demonstrated in Figure 37, the successful integration of the real prosumer into the Cyprus grid's digital twin is verified.

7.4 Validation of the coordination of the actual prosumer integration

The last part is related to the actual prosumer coordination by the ABCM-D platform to relieve distribution grid local congestion. For this experiment, the integration of the actual prosumer in the Cyprus power system digital twin is first ensured, and then the coordination of the actual prosumer is enabled through the ABCM-D platform. The demonstration results are presented in Figure 38, as captured by the WiseWire Cloud platform, and in Figure 38, as captured by the ABCM-D real-time monitoring tool.

The demonstrated scenario corresponds to a 1-hour scenario (between 13:20 and 14:20) where the actual prosumer was coordinated by the ABCM-D platform to relieve the congestion of the Cyprus distribution grid (emulated within the digital twin).

7.4.1 Demonstration through the WiseWire platform

In Figure 38(a), the coordination reference signals ($\Delta P^{*}=DPref$, $\Delta Q^{*}=Dqref$) sent by the ABCM-D platform to the actual prosumer and the response (operation) of the actual battery system ($P_{B\text{-}a}=Pbss$ $Q_{B\text{-}a}=Qbss$) are presented. Figure 38(b) presents the actual prosumer total operation ($P_{P\text{-}tot\text{-}a}$, $Q_{P\text{-}tot\text{-}a}$), indicating the total power exchange between the prosumer and the grid, where the battery operation is also included. It is noted that for representation and validation purposes, the ABCM-D platform sends to the WiseWire Cloud platform the active

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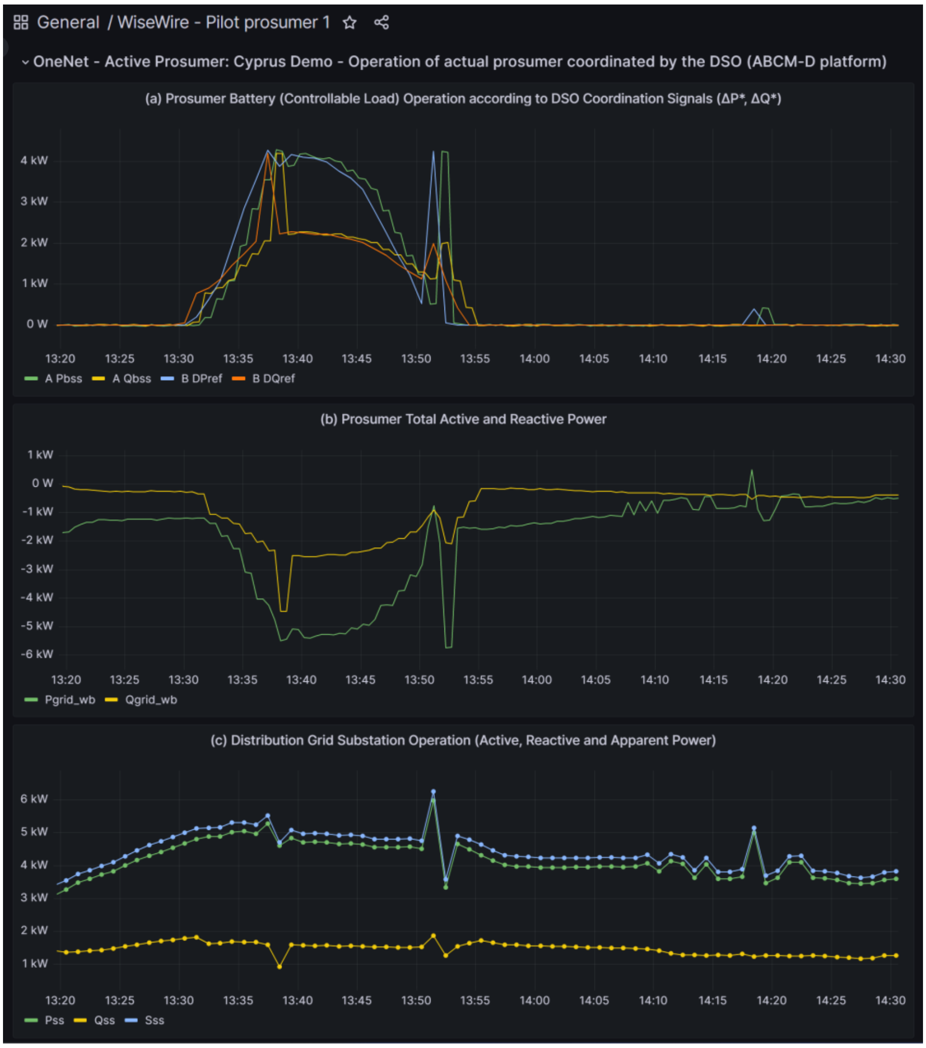

Figure 38: Demonstration results regarding the coordination of the actual prosumer within the Cyprus demo, as captured by the WiseWire cloud platform.

and reactive power measurements of the most congested phase of the distribution grid substation ($P_{S\text{-}DT}$ =Pss, $Q_{S\text{-}DT}$ = Qss), as received by the Cyprus grid digital twin, which are presented in Figure 38(c).

When the demonstration scenario starts, at 13:20, there is no congestion (overloading conditions) in the distribution grid, where a limit of 15 kVA is assumed for the specific low voltage distribution feeder (5kVA maximum limit in each phase). Therefore, until 13:31, there is no overloading condition, and the actual prosumer battery system is coordinated to zero active and reactive power injection in order to minimize activation cost since no flexibility is needed during this time.

Between 13:32 and 13:53 (and at 14:18), a congestion is observed in the distribution substation level since the most congested phase exceeds the assumed limit of 5 kVA. During this time window, the coordination SUC of the ABCM-D platform (coordination tool of Section 4.4.4) sends coordination signals (ΔP^*, ΔQ^*) to the battery

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system of the actual prosumer to achieve upward active and reactive power flexibility to locally serve part of the load with the goal of relieving congestion. The battery system of the actual prosumer receives these coordination signals and is able to adjust the battery system operation to track these reference signals with a settling time of 60 seconds as shown in Figure 38(a). The coordinated battery operation to provide upward flexibility affects the total prosumer active and reactive power, as shown in Figure 38(b), where a downward power flexibility is achieved for the prosumer interaction with the grid. As a result, the substation loading conditions were reduced allowing the operation of the low voltage distribution feeder without exceeding the 15 kVA limit (5 kVA limit for the most congested phase) as shown in Figure 38(c). It is noted that a slight violation of up to 10% may be observed when the demand profile presents a high positive ramping rate. This is attributed to the fact that a 1-minute control loop is used in the coordination tool of the ABCM-D platform which does not allow to capture the faster power deviations of the demand profile. Furthermore, spikes presented, e.g., at 13:52 or at 14:18, are due to the short time usage of some appliance in the actual prosumer that deviates suddenly the total distribution grid demand profile. These sudden changes on the profile are either only valid for 30-60 seconds or are compensated by the battery within 60 seconds.

It should be highlighted that without the coordination tool of the ABCM-D platform and the engagement of the actual prosumer for the active management of the distribution grid, overloading conditions of up to 30% were expected between 13:32 and 13:53 in the scenario presented in this demonstration (Figure 38). However, with the active coordination of the actual prosumer, the congestion and the overloading violation are reduced to 10% during the demand profile with high ramping rate (between 13:32-13:37) and to 0-1% between 13:38 and 13:53. As a result, an appropriate congestion management is achieved through the coordination solution of the OneNet project (ABCM-D platform) and through actual prosumer engagement.

7.4.2 Demonstration through the ABCM-D platform

In this sub-section, results collected from the Cyprus power grid digital twin and the ABCM-D platform are presented, as a cross-validation step for the demonstration results presented in Section 7.4.1. The results presented in Figure 39 are collected from the Cyprus grid digital twin concerning the per phase (each column) operation of substation (first row), battery (second row), and prosumer (third row). It is noted that in the ABCM-D platform the battery is assumed as a load, while in the WiseWire Cloud it is considered as a generation and thus both active and reactive power present a vice versa sign.

The cross-validation is achieved by comparing the results presented in Figure 38 and Figure 39, where an identical operation is recorded by both systems (WiseWire Cloud and ABCM-D platform). Furthermore, through the per phase operation demonstrated in Figure 39, it is clear that the coordination algorithm considers the most congested phase when upward/downward flexibility is requested by the active prosumer in order to allow all the phases to be within the substation limit. In the example of Figure 39, phase b is the most congested phase

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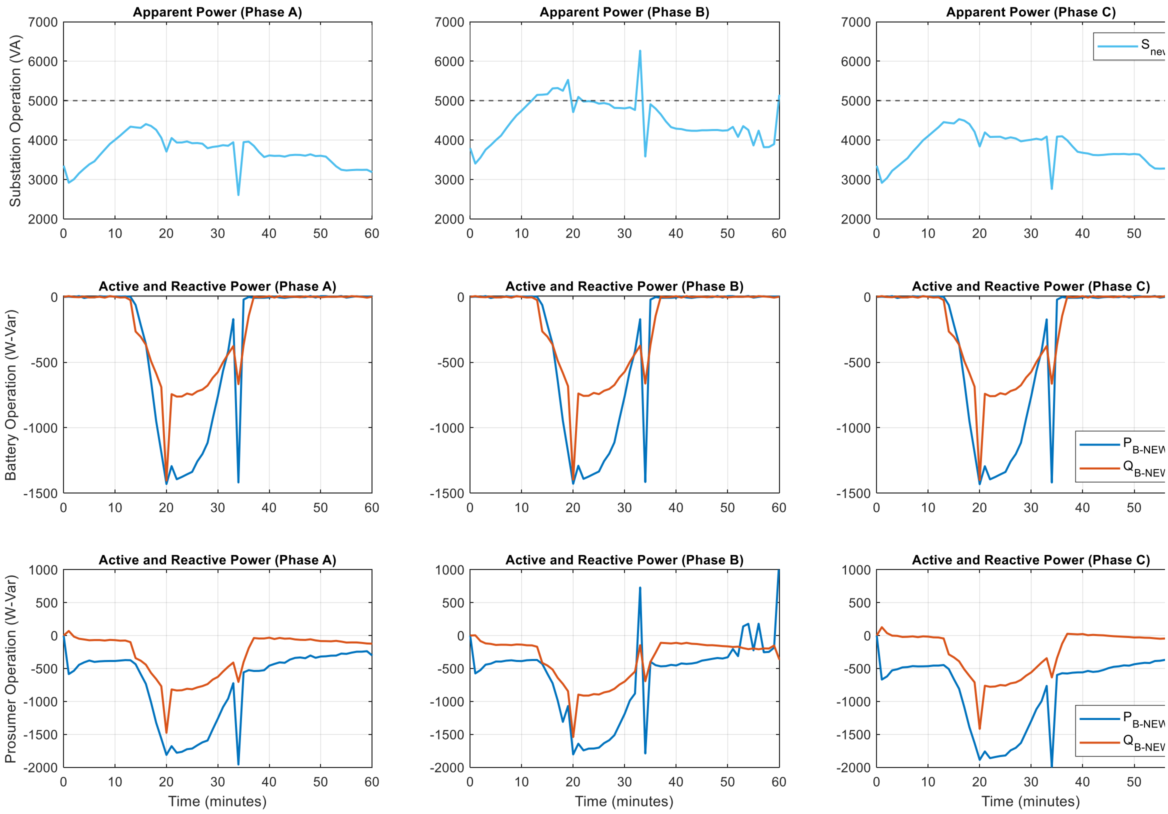

Figure 39: Cross-validation results regarding the coordination of actual prosumer by the ABCM-D platform to relieve congestion according to data obtained by the ABCM-D platform and the Cyprus grid digital twin.

and therefore the coordination solution requires from all the phases of the battery to provide up to 1.4 kW and up to 0.7 kVAr to manage the congestion and ensure that all the phases are within the limits at the substation level. Through this cross-validation the proper operation of the entire use case is validated considering more detailed measurements about the operation of the distribution grid digital twin.

Solutions that facilitate the coordination and active management of the distribution grid can intensely influence modern power grids. In this section, the online coordination of a prosumer by the DSO in order to relieve congestion in the distribution grid is effectively demonstrated within the Cyprus demo. Through this scenario, it is shown that the FSPs and prosumers can actively participate in the coordination of the distribution grid by providing ancillary services according to the new market scheme (NRT-DSO-AS market described in Section 5.1.2.3). Through this particular scenario of the OneNet Cyprus demo, it is illustrated that the DSO can exploit the FSPs' and prosumer's flexibilities to relieve congestion in a cost-effective manner and to avoid expanding or upgrading the wire infrastructure. Through this scenario, the proper operation of the monitoring and coordination system use cases of the Cyprus demo has also been validated in a relevant environment, where the digital twin and the actual prosumer are seamlessly integrated.

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8 Conclusions

In conclusion, the Cyprus demo within the OneNet project contributes to the enhancement of the stability, and efficiency of the Cyprus electricity system. Through the seamless collaboration among the key stakeholders and the innovative solutions that were developed, the demo has successfully showed the way how FSPs can contribute valuable flexibility services to the grid through their effective orchestration. This multifaceted initiative not only aligns with the overarching goal of transitioning towards a more sustainable power system but also exemplifies a comprehensive approach to addressing the challenges posed by the high penetration of Renewable Energy Sources (RES) in the islanded Cyprus power grid.

A cornerstone of this endeavour is the Cyprus power system digital twin that enables the creation of a testing, validation, and demonstration environment where the ABCM-T and ABCM-D platform are integrated in a hardware in the loop configuration. The Cyprus power system digital twin that includes the whole transmission and a part for the distribution level (MV and LV) runs in a real time simulator, emulating the actual operating condition of the Cyprus power system through the live feed of actual measurements from the grid.

Furthermore, the Active Balancing and Congestion Management platforms (ABCM-T and ABCM-D) have been implemented in order to assist the TSO and the DSO to achieve an appropriate, efficient and cost-effective operation of the Cyprus demo. The two platforms include four main tools namely the real-time monitoring, pre-qualification, FSP response evaluation, and distribution grid coordination. In more details, accurate and real time information about the grid operating conditions is enabled for the Cyprus digital twin by the real time monitoring tool. This information is used for the pre-qualification, FSP response evaluation and distribution grid coordination. In order to ensure that the provision of flexibility services by the FSPs located in the distribution grid will not congest the distribution grid, the pre-qualification tool provides MVA limits for each HV/MV substation to the FCR global TSO market. These limits are provided hourly and should be respected in the clearing procedure of the market. Furthermore, the response of the FSPs after the provision of ancillary services are evaluated through the FSP response evaluation. This tool checks if the FSP provided the appropriate amount of active power deviation for frequency support during a grid disturbance and the requested active/reactive power when they received the coordination signals by the distribution grid coordination tool. The coordination signals are related to the upward/downward active and reactive power flexibility as well as to the phase balancing services, which are generated by the distribution grid coordination tool to manage congestion. In the activities of the Cyprus demo, user interfaces have been created as well to facilitate the user-friendly interaction with the tools and essentially with the two platforms.

The Cyprus demo includes also an innovative ancillary services market framework that was designed and equipped with market clearing algorithms. This framework plays a pivotal role in trading flexibility services, which are used by the operators to manage their grids for relieving congestion and ensuring a reliable and stable

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operation even under extreme scenarios. The market framework that was developed in the Cyprus demonstration encompasses intra-day TSO market that deals with the frequency containment reserves, and near real time DSO market that procures flexibility services for grid congestion management. Through the innovative market framework, the participation of the FSPs located in the distribution grid is facilitated enhancing the overall grid flexibility of the Cyprus system.

Nevertheless, Cyprus demo fosters a collaborative and interconnected energy ecosystem through the integration of the OneNet system that serves as a facilitator for seamless information exchange among different stakeholders. In particular, the TSO, the DSO, the market operator, and FSPs collaborates for the effective operation of the grid. Lastly, the inclusion of an actual residential prosumer within the demo serves as a tangible testament to the project's practical applicability and relevance in the real world. This living example showcases the potential for individuals to actively participate in the grid management process to cost-effectively relieve congestion.

The key results of the Cyprus demo namely the digital twin power system, the tools of the ABCM platforms, the ancillary electricity market framework, and the ABCM platforms are going to be exploited extensively after the end of the OneNet project. It is envisioned that the Cyprus digital twin power system and the HiL framework can be used for extensive studies for both the TSO and DSO in Cyprus, while it can be the environment for testing new services, technologies, and methods before their actual application to power systems. Since the electricity market in Cyprus has not established yet, the developed ancillary market framework can be used as a basis for enabling the FSPs in the Cyprus power system to participate in the market for the provision of ancillary services. Moreover, a business plan will be developed for the ABCM platforms and the innovative tools us demo to examine and facilitate the commercialization of these key exploitation results.

The Cyprus demo is not merely a demonstration of innovative solutions but a holistic approach for addressing the challenges of modern power systems with high-RES penetration. It promotes the sustainability, collaboration, and adaptability. The validation and evaluation framework of the Cyprus demo will be completed with an extensive set of KPIs, that will provide invaluable insights into the project's accomplishments. The results of this evaluation will showcase the Cyprus demo's significance in the ongoing transformation of the energy sector.

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