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TABLE OF CONTENTS

EXECUTIVE SUMMARY	8
1. INTRODUCTION	10
1.1 EU-SYSFLEX PROJECT	10
1.2 WP8 AND FRENCH DEMONSTRATION	10
1.3 CONTEXT AND OBJECTIVES	11
1.4 WP8 REPORTS	12
2. DEMONSTRATION SET-UP AND MAIN DEVELOPMENTS.....	13
2.1 SET-UP OF HARDWARE COMPONENTS.....	13
2.1.1 ANGLURE WIND FARM.....	13
2.1.2 BATTERY STORAGE – E-STORAGE 2300.....	14
2.1.3 CONCEPT GRID.....	15
2.1.4 PV PANELS.....	17
2.2 DEVELOPMENT OF SOFTWARE AND CONTROL MODULES	17
2.2.1 RENEWABLE GENERATION FORECASTING TOOLS.....	18
2.2.2 CENTRALISED OPTIMIZATION AND CONTROL – ENERGY MANAGEMENT SYSTEM (EMS)	19
2.2.3 LOCAL CONTROLLERS OF INDIVIDUAL ASSETS	24
2.2.4 HUMAN-MACHINE INTERFACE	27
2.3 IMPLEMENTATION OF THE COMMUNICATION INFRASTRUCTURE.....	29
2.3.1 COMMUNICATION ARCHITECTURE.....	29
2.3.2 IT INTERFACES AND SOLUTIONS	31
2.3.3 COMMUNICATION INFRASTRUCTURE CONFIGURATIONS	33
2.3.4 PREPARATION OF THE DATABASE.....	35
3. OFFLINE SIMULATION TESTING AND ASSESSMENT OF ECONOMIC KEY PERFORMANCE INDICATORS	36
3.1 ADVANCED OFFLINE SIMULATION PLATFORM FOR VPP OPERATION	36
3.1.1 STRUCTURE OF THE PLATFORM.....	36
3.1.2 SIMULATION PROCESS.....	37
3.1.3 PRACTICAL APPLICATIONS OF THE PLATFORM	38
3.2 DAY-AHEAD SCHEDULING AND IMPACT OF OPTIMIZATION APPROACHES	38
3.2.1 DETERMINISTIC SCHEDULING USING PERFECT FORECASTS.....	39
3.2.2 IMPACT OF THE FORECAST ERRORS.....	40
3.2.3 STOCHASTIC SCHEDULING USING PROBABILISTIC FORECASTS.....	42
3.3 ILLUSTRATION OF THE VPP OPERATION OVER A ONE-DAY SIMULATION.....	45
3.3.1 DESIGN OF THE DAY-AHEAD SCHEDULES.....	46
3.3.2 SIMULATION OF THE STC OPERATION AND VPP BEHAVIOUR OVER THE FIRST 3 HOURS OF THE DAY	47
3.3.3 GLOBAL PERFORMANCE OVER THE DAY WITH INTRADAY RESCHEDULING EVERY 4 HOURS	48
3.4 ASSESSMENT OF ECONOMIC KPIS BASED ON OFFLINE SIMULATIONS	50
3.4.1 VALUE OF MULTI-SERVICES PROVISION.....	50
3.4.2 INTEREST OF THE FCR PROVISION BY MULTI-RESOURCES.....	53
3.4.3 INTEREST OF STOCHASTIC PROGRAMMING APPROACHES.....	55
4. EXPERIMENTAL DEMONSTRATION OF THE MULTI-SERVICE VPP AND ASSESSMENT OF TECHNICAL KEY PERFORMANCE INDICATORS ..	58
4.1 DEMONSTRATION OF FLEXIBILITY SERVICES PROVISION.....	58
4.1.1 FREQUENCY CONTAINMENT RESERVE.....	58
4.1.2 OTHER FLEXIBILITY SERVICES	65
4.2 DEMONSTRATION OF THE FULL-CHAIN OF OPERATION.....	73
4.2.1 ILLUSTRATION OF THE VPP OPERATION	73
4.2.2 ASSESSMENT OF TECHNICAL KPIS.....	81
5. KEY FINDINGS AND RECOMMENDATIONS.....	93
5.1 CONCLUSIONS.....	93
5.2 LESSONS LEARNT AND RECOMMENDATIONS.....	95
5.2.1 WIND FREQUENCY CONTROL.....	95
5.2.2 VPP OPERATION.....	95
6. COPYRIGHT	97
7. BIBLIOGRAPHY.....	98

LIST OF FIGURES

FIGURE 1. EU-SYSFLEX GENERAL WORK PACKAGE STRUCTURE	10
FIGURE 2. MEANS AND FACILITIES OF THE MULTI-RESOURCES MULTI-SERVICES DEMONSTRATION	13
FIGURE 3 : WIND FARM " ANGLURE 2"	14
FIGURE 4: COMPLETED BESS INSTALLED IN 2019	15
FIGURE 5. EXAMPLE OF EQUIPMENT TESTED AT CONCEPT GRID	16
FIGURE 6. REAL-TIME SIMULATION PLATFORM OF CONCEPT GRID	16
FIGURE 7. DETERMINISTIC FORECAST (RED SOLID LINE) AND PROBABILISTIC FORECAST SHOWING THE 1%, 5% ... 95% AND 99% QUANTILES OF THE FORECAST (RED DASHED LINES) AND WIND FARM ACTUAL POWER (BLACK LINE WITH CIRCLES) OVER THE DAY OF 2018-02-04: DAY-AHEAD FORECAST (LEFT) AND 30-MINUTE-AHEAD FORECAST (RIGHT).....	18
FIGURE 8. PV FORECASTING MODELS	19
FIGURE 9. BASE MODEL OF THE VPP IN THE SCHEDULER SOFTWARE.....	20
FIGURE 10. OPERATION TIMELINE OF THE SHORT-TERM CONTROL.....	24
FIGURE 11. CONTROL LAYERS OF THE FRENCH DEMONSTRATION.....	25
FIGURE 12. FCU E2 CONTROLLER: CONTROL CABINET (LEFT); ANGLURE WIND FARM STRUCTURE (RIGHT).....	26
FIGURE 13. HMI PAGES FOR CONTROL AND SUPERVISION	28
FIGURE 14. HMI PAGES FOR VPP MONITORING	28
FIGURE 15. COMMUNICATION ARCHITECTURE OF WP8 DEMONSTRATION.....	30
FIGURE 16: DEMONSTRATION IT ARCHITECTURE	32
FIGURE 17. IEC 61850 MODELING STRUCTURE EXAMPLE	33
FIGURE 18. OFFLINE SIMULATION PLATFORM TO TEST THE FRENCH VPP	37
FIGURE 19. (A) DAY-AHEAD MARKET PRICE. (B) DAY-AHEAD SCHEDULE FOR ENERGY ARBITRAGE	39
FIGURE 20. DAY-AHEAD SCHEDULE OF THE BATTERY: (A) POWER, (B) STATE OF CHARGE	40
FIGURE 21. DETERMINISTIC DAY-AHEAD FORECAST AND ASSOCIATED GENERATION: (A) PV, (B) WIND, AND (C) PV + WIND.	40
FIGURE 22. (A) PRICES OCCURING IN THE VPP FULL INCOME. (B) DAY-AHEAD SCHEDULE VERSUS ACTUAL ENERGY OF THE VPP.....	41
FIGURE 23. DAY-AHEAD PROBABILISTIC GENERATION FORECASTS	42
FIGURE 24. EXAMPLES OF STOCHASTIC SCENARIOS GENERATED FROM PROBABILISTIC GENERATION FORECASTS:	43
FIGURE 25. DAY-AHEAD SCHEDULE FOR ENERGY ARBITRAGE WHEN CONSIDERING PROBABILISTIC GENERATION FORECASTS:	44
FIGURE 26. (A) MARKET PRICES AND IMBALANCE PENALTIES, (B) DAY-AHEAD SCHEDULES FOR THE VPP AND THE BESS	46
FIGURE 27. FORECASTED AND ACTUAL GENERATION: (A) PV, (B) WIND.....	46
FIGURE 28. (A) (B) BESS POWER AND SOC WITH BASIC STC STRATEGY, (C) (D) BESS POWER AND SOC WITH SOC CONTROL STRATEGY.....	47
FIGURE 29. (A) SCHEDULED AND ACTUAL VPP ENERGY, (B) DOWNWARD FCR SCHEDULED FOR THE BESS, (C) DOWNWARD FCR SCHEDULED FOR THE WIND FARM.....	48
FIGURE 30. (A) SCHEDULED AND ACTUAL BESS POWER, (B) SCHEDULED AND ACTUAL BESS SOC, AND GRID FREQUENCY	49
FIGURE 31. EXTRACT OF THE 5-WEEK SCHEDULES: (A) SPOT AND FCR PRICES, (B) SCHEDULED BESS FCR.....	52
FIGURE 32. EXTRACT OF THE 5-WEEK SIMULATIONS: (A) SCHEDULED AND ACTUAL BESS POWER, (B) SCHEDULED AND ACTUAL BESS POWER SOC.....	52
FIGURE 33. EXTRACT OF THE 5-WEEK SIMULATIONS: IMBALANCES WHEN FCR IS PROVIDED BY BOTH RESOURCES	55
FIGURE 34. EXTRACT OF THE 5-WEEK SIMULATIONS: IMBALANCES WHEN FCR IS PROVIDED BY STORAGE ALONE	55
FIGURE 35. COMPARISON BETWEEN DETERMINISTIC AND STOCHASTIC PROGRAMMING: (A) DAY-AHEAD SCHEDULES, (B) IMBALANCES	57
FIGURE 36. ILLUSTRATION OF WIND RESERVE CONSTITUTION AND DELIVERY	59
FIGURE 37. PROVISION OF FCR BY STORAGE: (A) GRID FREQUENCY, (B) POWER AT POC, SOC CONTROL POWER AND FCR POWER	60
FIGURE 38. WIND FCR DELIVERY OF 1 MW @ 50 MHZ (EXTRACTED DURATION: 14 MINUTES)	61
FIGURE 39. PERFORMANCE ASSESSMENT OF FCR GAIN	62
FIGURE 40. WIND FCR DELIVERY OF 1 MW @ 200 MHZ (EXTRACTED DURATION: 30 MINUTES)	63

FIGURE 41. WIND FCR GAIN PERFORMANCE ASSESSMENT: (A) DIFFERENCE BETWEEN THE ACTUAL AND THE EXPECTED POWER, (B) ESTIMATED FCR GAIN	64
FIGURE 42. AAP ESTIMATION ERROR IMPACTING FCR PROVISION PERFORMANCE	64
FIGURE 43. FAST FREQUENCY RESERVE PARAMETER CHART	66
FIGURE 44. FAST FREQUENCY RESPONSE OF THE STORAGE.....	67
FIGURE 45. AUTOMATIC RESTORATION RESERVE PROVIDED BY THE STORAGE: (A) POWER AT POC, SOC CONTROL POWER AND FRR RESPONSE, (B) FRR SETPOINT (LEVEL N), (C) STATE OF CHARGE	68
FIGURE 46. AUTOMATIC RESTORATION RESERVE PROVIDED BY THE WIND FARM: (A) ESTIMATED AVAILABLE ACTIVE POWER AND ACTUAL POWER AT POC, (B) FRR RESERVE, (C) FRR SETPOINT AND ACTUAL RESPONSE	69
FIGURE 47. CONTROL PARAMETERS AND REGULATION LAW FOR MULTI-SERVICE PROVISION	70
FIGURE 48. MULTI-SERVICE PROVISION BY BESS IN REAL CONDITIONS	70
FIGURE 49. RAMP RATE CONTROL OF RENEWABLE GENERATION USING STORAGE.....	71
FIGURE 50. RAMP RATE OF VPP V.S. WIND GENERATION ONLY	72
FIGURE 51. VPP SCHEDULING ON OCT. 22, 2021	74
FIGURE 52. DISTRIBUTION OF THE FCR ON THE BATTERY AND THE WIND FARM	75
FIGURE 53. ACTUAL POWER OF THE VPP AND EXPECTED FCR RESPONSE	76
FIGURE 54. BATTERY POWER AND SOC	77
FIGURE 55. ZOOM ON THE FCR PROVISION BY THE BATTERY	77
FIGURE 56. EXPECTED AND ASSESSED FCR RESPONSE FROM THE BESS	78
FIGURE 57. AVAILABLE WIND POWER AND ACTUAL GENERATION	79
FIGURE 58. EXPECTED AND ASSESSED FCR RESPONSE FROM THE WIND FARM	80
FIGURE 59. IMPACT OF THE OVERESTIMATION OF THE WIND AAP ON FCR RESPONSE	81
FIGURE 60. FCR GAIN ASSESSMENT FOR THE TEST ON OCT. 22	83
FIGURE 61. COMPARISON OF THE ASSESSED AND EXPECTED WIND FCR RESPONSE FOR THE TEST ON OCT. 20	85
FIGURE 62. FCR RESPONSE OF THE VPP AS A FUNCTION OF GRID FREQUENCY (TEST ON OCT. 22).....	86
FIGURE 63. ANALYSIS OF THE LACK OF POWER FOR FCR RESPONSE IN CASE THE FREQUENCY REACHES 50.2 HZ.....	88
FIGURE 64. ANALYSIS OF THE LACK OF POWER FOR FCR RESPONSE IN CASE THE FREQUENCY REACHES 50.2 HZ.....	89
FIGURE 65. OCCURRENCE OF THE COMMUNICATION PROBLEM ON DEC. 9, 2021	91

ABBREVIATIONS AND ACRONYMS

AC	Alternative Current
API	Application Programming Interface
BESS	Battery Energy Storage System
BCS	Battery Control System
CG	Concept Grid
DC	Direct Current
DEIE	Dispositif d'Echange d'Informations d'Exploitation
DER	Distributed Energy Resources
DSO	Distribution System Operator
ECMWF	European Centre for Medium-Range Weather Forecasts
EDF	Electricité de France
EMS	Energy Management System
E-SCU	E-Storage Control Unit
ESS	Energy Storage Systems
EU	European Union
FACTS	Flexible Alternative Current Transmission System
FCDA	Functional Constrained Data Attribute
FCR	Frequency Containment Reserve
FCU	Farm Control Unit
FFR	Fast Frequency Response
FRR	Frequency Restoration Reserve
GED	Grid Edge Device
HMI	Human-Machine Interface
IED	Intelligent Electronic Devices
ICT	Information and communication technology
IPsec	Internet Protocol Security
IT	Information Technology
KPI	Key Performance Indicator
LD	Logical Device
LN	Logical Nodes
LV	Low Voltage
MILP	Mixed Integer Linear Programming
MMS	Manufacturing Message Specification
MV	Medium Voltage
ODBC	Open Database Connectivity
OPS	Operational Planning Scheduler
PMB	Project Management Board
PoC	Point of Connection
PV	Photovoltaic
QoS	Quality of Service
RES	Renewable Energy Sources
RES-E	Renewable Sources of Electricity
RRC	Ramp Rate Control
RT	Real-time

RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SCL	Substation Configuration description Language
SFTP	SSH File Transfer Protocol
SO	System Operators
SoC	State of Charge
STC	Short-Term Control
TCP	Transmission Control Protocol
TSO	Transmission System Operator
UDP	User Datagram Protocol
VPP	Virtual Power Plant
VRG	Variable Renewable Generation
WP	Work Package

EXECUTIVE SUMMARY

In the context of the energy transition that imposes changes in European power systems and a consequent increase in flexibility requirements, an aggregation approach based on the concept of Virtual Power Plant (VPP) has been proposed in the Work Package (WP) 8 demonstration of the EU-SysFlex H2020 project. This demonstration aims at developing and experimenting an innovative multi-services multi-resources control and operation approach. The demonstration was set to provide technical evidence of how the timely provision of the services could be achieved by distributed resources that will be largely present in the future European system, as well as how these new actors could jointly participate in different energy and flexibility markets through an innovative portfolio management.

The VPP includes several decentralized assets including a 12-MW windfarm, a PhotoVoltaic (PV) generation unit and a 2-MW/3-MWh Battery Energy Storage System (BESS). Thanks to a central Energy Management System (EMS), the different assets were managed in a coordinated and optimal manner. Based on multiple criteria such as weather forecasts, energy and services market prices and availability of assets, the EMS developed proved capable of providing optimal energy and multi-service schedules for the VPP and of allocating frequency reserve on the controlled assets, at regular intervals, by considering the most recent forecasts and measures.

For the purpose of the demonstration, a full IEC-61850-based and hardware-agnostic communication platform was developed presenting several advantages such as the flexibility to manage the software, firmware and configurations on remote devices and the increased level of cybersecurity. Its reliability has been proven during the tests. Moreover, its ability to enable a simple and standardized integration of new assets into the VPP management fosters the scalability and the replicability of the demonstrated solutions.

Both offline and online testing were successfully achieved, respectively by performing intensive simulations on an advanced offline simulation platform and by carrying out local and full-chain tests in real conditions. The focus of the tests was on the assessment of frequency reserves provided by individual resources (wind generation and battery storage) and by the whole VPP, although other flexibility solutions such as ramp rate control were also demonstrated. In addition, the capability to provide simultaneously multiple services was carefully considered in the controllers' design and evaluated through experiments. Globally, the performance of the assessed services complied with the requirements imposed by the system operator. The fast responses of both wind generators and storage led to very high performances in terms of dynamics.

The following outcomes were highlighted during the demonstration work:

- The provision of frequency containment reserve (FCR) in addition to energy helps increasing the VPP revenue and also enables the VPP to effectively contribute to the resilience of the power system.
- It is beneficial to have a joint participation of the wind farm and the storage in FCR provision, as it not only gives the BESS more flexibilities for energy arbitrage, but also highly increases the economic opportunities for wind generation while avoiding costly renewable generation losses.

- The availability of the reserve provided by the VPP is greatly dependent on the accuracy of the wind forecasts.
- The estimation precision of the wind instantaneous available active power (AAP) is another key factor to ensuring the performance of the frequency reserve provided, notably in terms of FCR control gain assessment.

In addition to the other three WP8 annual progress reports published in previous years, this final report describes main developments of the demonstration, test procedures, overall results and key performance indicators assessment, and provides a summary of the key findings and lessons learned.

1. INTRODUCTION

1.1 EU-SYSFLEX PROJECT

By 2030, the European Union has committed to deliver at least 50% of its electricity consumption from renewable sources of electricity (RES-E), much of this will come from wind and solar. As a result, the electricity supply is becoming more complex, creating uncertainties and technical challenges not previously seen in the pan-European electricity system.

EU-SysFlex is a Horizon 2020-funded project which addresses these challenges by identifying and demonstrating new types of system and flexibility services. The project aims to identify the long-term needs as well as the technical scarcities of the future power system and will ultimately create a long-term roadmap of actions for Europe to facilitate the large-scale integration of new technologies and capabilities.

The EU-SysFlex project is structured into twelve work packages (Figure 1), covering different aspects of the innovation process, from the development of new approaches for integrating large-scale renewable energy and testing pilot installations, to an analysis of the regulatory requirements and the development of viable business models and policy recommendations.

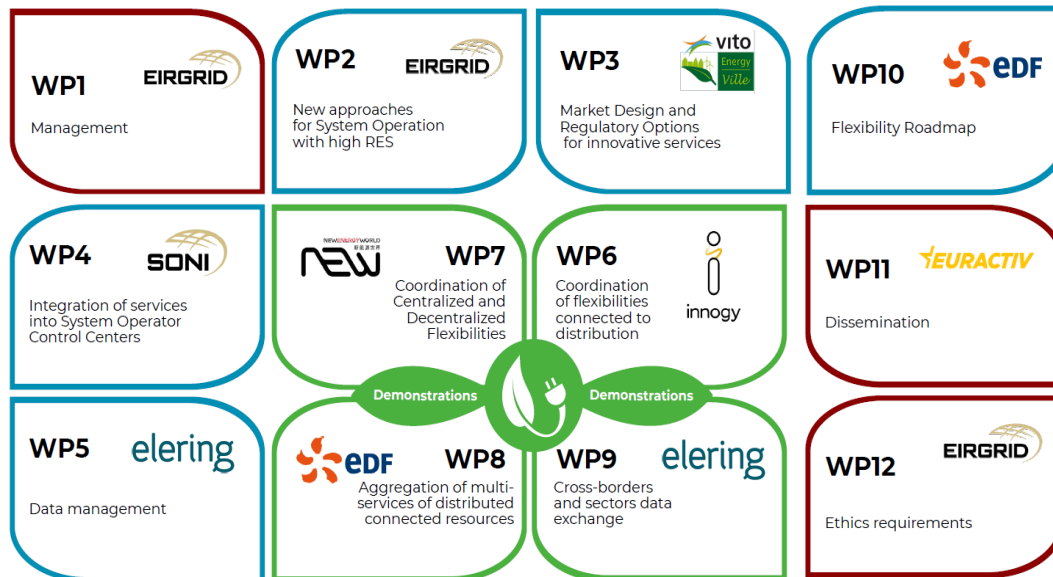


FIGURE 1. EU-SYSFLEX GENERAL WORK PACKAGE STRUCTURE

1.2 WP8 AND FRENCH DEMONSTRATION

Increasing the flexibility of the pan-European electricity system requires a comprehensive and all-encompassing vision that extends across a broad portfolio of new approaches, solutions and technologies. EU-SysFlex provides this by demonstrating different business use cases in seven field tests at all system levels and across Europe: Portugal, Germany, Italy, Finland, France and Estonia.

An aggregation approach based on the concept of **Virtual Power Plant (VPP)** has been proposed in the Work Package 8 (WP8) demonstration of the EU-SysFlex project, which aims at developing and experimenting an innovative **multi-services and multi-resources** control approach. The demonstration was set to provide technical evidence of how the timely provision of the services could be achieved by the distributed resources that will be largely present in the future European system, as well as how these new actors could jointly participate in different energy and flexibility markets through a portfolio management.

The outcomes of this WP provide to the project an enhanced flexibility provision perspective by optimally coordinating proved capabilities of distributed renewable generators as well as storage devices. This can contribute to the European power system's higher needs in terms of flexibility and is also aligned with the EU objective of increasing the integration of renewable sources.

1.3 CONTEXT AND OBJECTIVES

To guarantee the security and reliability of power systems with high penetration of sources interfaced by power electronics, the provision of ancillary services such as frequency and voltage regulations shall be supplied not only by conventional synchronous units but also by variable Renewable Energy Sources (RES) and/or Energy Storage Systems (ESS). From the local point of view, two conditions are necessary to increase the profitability and reliability of the services provided by such resources: 1/ the provision of multiple services that mobilize the full power/energy capacity of any resource, and 2/ the combination of different units' abilities to compensate for unfavourable wind/solar conditions or limited storage capacity.

In this context, a VPP is developed and experimented in France in WP8. The considered VPP includes a 12-MW wind farm, a 2-MW/3-MWh Battery ESS (BESS) and PhotoVoltaic (PV) panels. The main idea is to design a bilayer Energy Management System (EMS) and advanced local controllers that supervise the VPP operation and efficiently provide the following services to the power system (Table 1):

- Frequency support, i.e., **Fast Frequency Response (FFR)**, **Frequency Containment Reserve (FCR)** and **Frequency Restoration Reserve (FRR)**, as specified in [1];
- Flexibility solutions, such as **ramp rate control** of the VPP power and **shaving** of renewable generation.

It is expected to enhance the performance and reliability of the services procured from the VPP, compared to that from individual assets, and to help increase the economic gain for the VPP's operation thanks to additional revenue streams, from one or, more likely, from several levels of the electricity value chain.

Categories	Services
Frequency support services	Fast Frequency Response (FFR)
	Frequency Containment Reserve (FCR)
	Frequency Restoration Reserve (FRR)
Flexibility solutions	Ramp-rate control
	Peak shaving
Energy arbitrage as an aggregator	

TABLE 1. SERVICES PROVIDED BY THE WP8 MULTI-RESOURCES VPP¹

The partners involved in this demonstration are **EDF R&D**, including several research teams, and **ENERCON**, with also several branches cooperating for the needs of the demonstration work. The main objectives of the WP8 demonstration are to:

- demonstrate the technical feasibility of performing optimal management and coordinated control of the multi-resources VPP to provide multi-services to the power system;
- assess the performances of different services and flexibility solutions that can be procured from the aggregator by considering the grid codes' requirement.

1.4 WP8 REPORTS

An annual feedback report of WP8 is scheduled to be drawn up to present the development progress of the demonstration:

- D8.1 report published in October 2018 [2] described in detail the technical specifications.
- D8.2 report published in November 2019 [3] presented the installation and the commissioning of the hardware components as well as the first implementation of several control and communication modules.
- D8.3 report published in January 2021 [4] presented progress updates on software and algorithm development as well as first experimental results.

As the final report of the French demonstration, the present report:

- summarizes main developments on hardware, software and communication systems (Chapter 2),
- presents the offline simulation testing and the assessment results of the related economic key performance indicators (Chapter 3),
- presents experimental results of the VPP demonstration and the assessment results of the related technical key performance indicators (Chapter 4),
- provides conclusions, recommendations and lessons learnt from the demonstration work (Chapter 5).

¹ It should be noted that an adaptation of the demonstration scope has been applied in WP8 and reactive power services specified in [2] at the beginning of the project could finally not be tested in the French VPP due to delays caused by the Coronavirus (COVID-19) pandemic and other technical interventions related to the battery cells' security and performance.

2. DEMONSTRATION SET-UP AND MAIN DEVELOPMENTS

2.1 SET-UP OF HARDWARE COMPONENTS

The main facilities and testing assets for the French demonstration are shown in Figure 2. **This VPP is composed of a 12-MW wind farm, a 2-MW / 3-MWh battery storage and photovoltaic panels** and is mainly implemented at EDF privately owned Concept Grid (CG), apart from the wind farm being at a remote location and connected to the French public distribution grid [5].

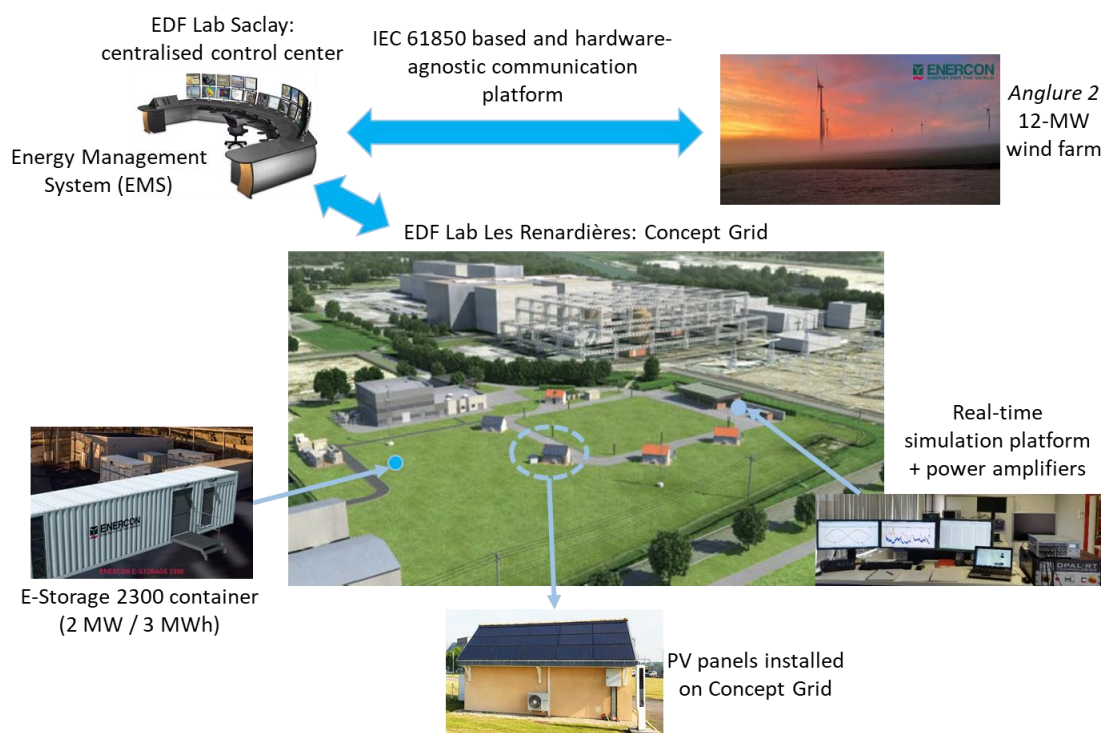


FIGURE 2. MEANS AND FACILITIES OF THE MULTI-RESOURCES MULTI-SERVICES DEMONSTRATION

2.1.1 ANGLURE WIND FARM

For the purpose of demonstration, ENERCON makes available the owned wind farm *Anglure 2*, located in the department of "Marne", in the community of Saron-Sur-Aube, about 120 km south-east of Paris (Figure 3). Commissioned in September 2015, *Anglure 2* is generating 30 000 MWh/year and comprises 6 x 2000-kW turbine of type E82 (82-meters rotor diameter) for a total installed power of 12 MW. Each wind turbine is based on a full converter technology with FACTS (Flexible Alternative Current Transmission System), which is a suitable solution for integration into the grid.



FIGURE 3 : WIND FARM " ANGLURE 2"

During the demonstration work, an enhanced wind farm control unit FCU (Farm Control Unit) dedicated to providing grid services has been designed and implemented, to replace the previous RTU (Remote Terminal Unit) wind farm controller. The newly developed FCU allows a much faster response time of the wind farm as it communicates directly with the wind turbines (and conversely to the RTU which communicates through the "slow" SCADA System). The capability of responding to the eventual requests from the French Distribution System Operator (DSO) ENEDIS (e.g. active power curtailment, WF disconnection, etc.) through the dedicated DEIE communication interface [6] was preserved. More details are described in Section 2.2.3.1 on the FCU controller.

2.1.2 BATTERY STORAGE – E-STORAGE 2300

A full storage system including a 2MW / 3MWh lithium-ion battery as well as a power conversion system are used for the EU-SysFlex demonstration (Figure 4). The BESS (Battery Energy Storage System) consists of the following main components:

- A battery container
- An E-Storage 2300 converter container
- Subordinate control systems (standard control cabinets)



FIGURE 4: COMPLETED BESS INSTALLED IN 2019

The Li-Ion battery is located in a 45-foot container, consisting of 42 racks. Each battery rack consists of 12 battery modules. Six battery racks are connected in parallel and form a battery bank. The complete system therefore consists of seven battery banks. Each battery bank is corresponding to the output of one DC-DC converter of the E-Storage 2300. The cell chemistry is based on graphite and NMC, manufactured by LGChem. The container was constructed and manufactured as a turn-key unit by the German battery manufacturer Hoppecke. The control of the battery units is realized by the E-Storage 2300, which ensures controlled charging and discharging.

Based on proven ENERCON power components, the E-Storage 2300 consists of a bidirectional inverter within a 40-foot container and serves as an intelligent interface technology for DC-batteries of all kind. The E-Storage 2300 is connected to the Medium Voltage (MV) grid, thus containing the hardware interface (transformer and MV switchgear) between the electrical grid and the DC power storage. The power cabinets transform the alternating current coming from the transformer into direct current and the direct current coming from the DC-DC cabinets into alternating current. The control cabinet contains the monitoring unit for the grid safety circuit. Fiber-optic cables transmit the signals for the grid, ENERCON SCADA and between the ENERCON storage control unit and the battery container.

ENERCON and EDF have jointly worked to prepare all the operations for the containers' installation and the connection to the grid. In January 2019, the two containers were successfully installed at EDF Concept Grid. A comprehensive commissioning test procedure was then carried out. That was an integrated collaborative work of LGChem, Hoppecke and ENERCON, together with EDF. After several test series and necessary technical interventions, the installation was finally proven compliant and the commissioning was passed. Details on the BESS design descriptions, installation procedure and commissioning test results can be found in a previous WP8 report [3].

2.1.3 CONCEPT GRID

Concept Grid has been set up by EDF R&D in the site of Les Renardières south-east of Paris. It was developed to study the integration of renewable energy resources (RES) in the electric system as well as new uses such as

electric vehicles or heat pumps [7]. Fed by a fully dedicated 63/20 kV transformer, CG includes 3 km of MV network (overhead lines and underground cables) supplying 7 km of LV (Low Voltage) network. One of the goals is to replicate the real conditions of an electric system operation. Representativeness is also brought by a residential neighbourhood of five 20 m² houses, fitted with state-of-the-art equipment: smart meters, remote controlled household appliances, reversible heat pumps, photovoltaic (PV) panels, terminal for electric vehicles, etc. Concept Grid is designed to take place half-way between laboratory tests and experiments in the field, where it is possible to conduct, in complete safety, complex testing campaigns that would be difficult to be performed in a real system. This open environment has been designed for many types of tests, becoming a privileged place for many stakeholders, from universities to equipment suppliers or network operators (Figure 5).



FIGURE 5. EXAMPLE OF EQUIPMENT TESTED AT CONCEPT GRID

CG contains also a Real Time (RT) simulator (Figure 6) that interacts with the grids and the assets to perform various tests. The real time simulator is an OPAL-RT product that uses its "E-MEGA sim" license. The simulator uses an extension to control a 4-quadrant linear, 120 kVA power amplifier from Puissance Plus.

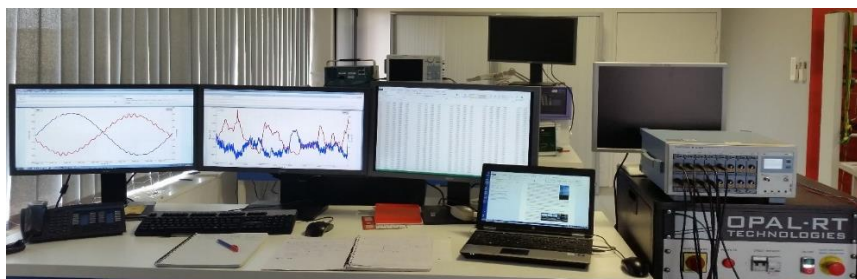


FIGURE 6. REAL-TIME SIMULATION PLATFORM OF CONCEPT GRID

In the EU-SysFlex French demonstration, the RT simulator serves as a communication interface between the CG control center and the BESS control cabinet through Modbus protocol, so that local constraints at the distribution grid, where the storage is installed, can be considered by the VPP control and management at all times. Furthermore, this communication platform based on the RT simulator has been highly employed throughout all the local tests for validating the storage controller's performance, as it ensures the security of these tests performed at CG by enabling the monitoring of the real time behavior of the BESS.

2.1.4 PV PANELS

For the demonstration purpose, some of the kW-size PV panels installed at Concept Grid are used to emulate the power generation of a 6-MW industrial PV farm, by applying a corresponding gain at the total predicted and produced power output of these panels (Table 2).

Location	Mounting	Exposure	Brand	Model	Number of panels	Power per panel	Total power	Inverter (brand and power)
T33 House	Roof	South	France Watt	RT6(x5)-RT3(x10)	15 (5 + 10)	(5*200W) + (10*165W)	2650W	DELTA SOLIVIA 2500W

TABLE 2. TECHNICAL DESCRIPTION OF THE PV PANELS USED IN THE FRENCH DEMONSTRATION

The inverters of these panels are not able to be controlled by external active and reactive power setpoints and the only allowed operating mode is based on MPPT (Maximum Power Point Tracking). Thus, for the French demonstration, the emulated PV farm is included in the portfolio management of the VPP, however, it outputs always its maximum available power and does not participate in the provision of ancillary services.

In general, the capability of PV panels to contribute to frequency and voltage regulations has already been proven in the literature and by other demonstrations [8] [9] [10]. There are no specific technical difficulties to further consider the flexibilities of PV generation in the VPP centralised optimisation and control process, when PV panels at the local level are equipped with more advanced inverters and can execute the activation orders of the services provision.

2.2 DEVELOPMENT OF SOFTWARE AND CONTROL MODULES

To operate the VPP composed of multi-resources of different nature as a whole and to ensure the optimal coordination of multi-services provision, centralized control functions have been built, including renewable generation **forecasting tools** as well as the **Energy Management System (EMS)** providing both day-ahead / intraday optimized schedules and short-term program adjustment capacities. **Local controllers** of the BESS and the wind farm have also been improved and upgraded for the purpose of the demonstration. Furthermore, to ensure the monitoring of the VPP's operation during experimental tests, a **Human-Machine Interface (HMI)** has been dedicatedly designed and developed.

2.2.1 RENEWABLE GENERATION FORECASTING TOOLS

Existing renewable generation forecasting tools and functions developed by EDF R&D have been applied for the EU-SysFlex French demonstration. Models' training was performed using either historical measurements provided by ENERCON (for the wind generation) or carried out at Concept Grid (for the PV forecasting).

2.2.1.1 WIND GENERATION FORECASTING

Statistical relations between *Anglure 2* wind farm generation and meteorological forecast parameters are learned over a period of two years (2016-01-26 to 2018-01-28). These relations are then used daily to assess the output of the wind farm over the following days when a new meteorological forecast is available. Meteorological forecasts are provided by Météo France and the European Centre for Medium-Range Weather Forecasts (ECMWF). Real-time wind farm generation is used to correct the meteorological forecasts over a short horizon of 2 hours.

Two types of forecast are computed: a deterministic forecast is provided by the trained statistical model, while a probabilistic forecast takes into account not only the result of the statistical model but also the distribution of the forecast errors over the model training period. An example of wind forecast on February 4th, 2018 is illustrated in Figure 7. As can be seen from the figure, the closer to real time, the more accurate will be the forecast.

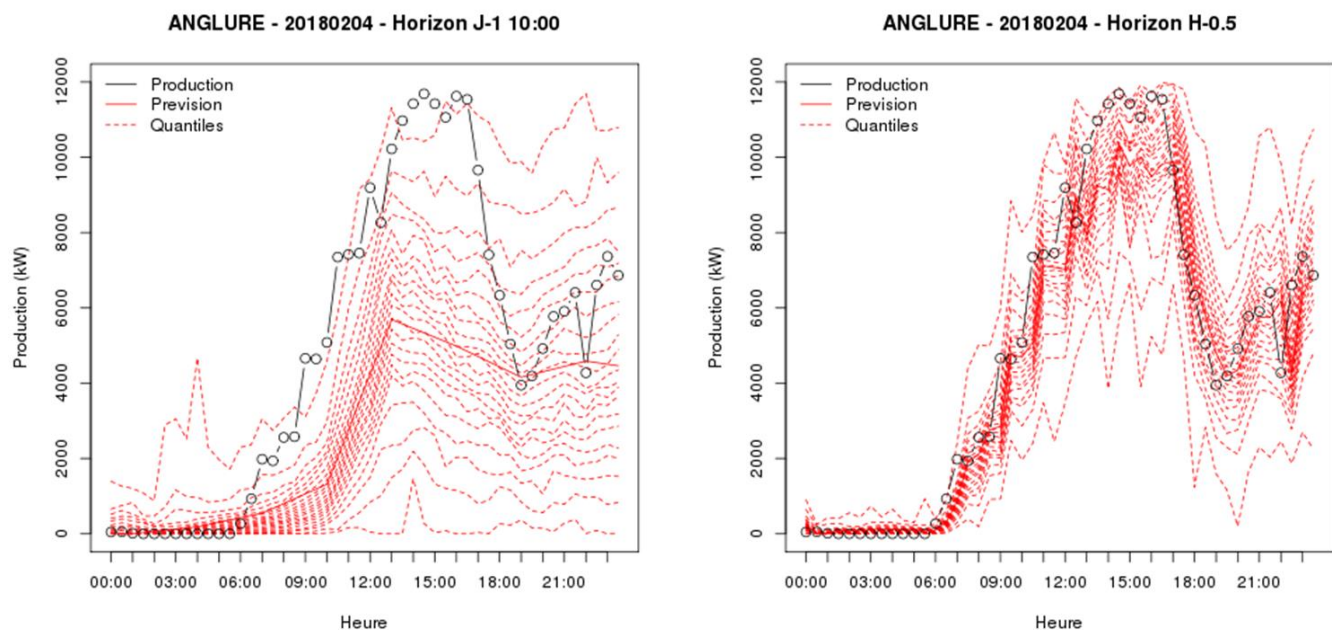


FIGURE 7. DETERMINISTIC FORECAST (RED SOLID LINE) AND PROBABILISTIC FORECAST SHOWING THE 1%, 5% ... 95% AND 99% QUANTILES OF THE FORECAST (RED DASHED LINES) AND WIND FARM ACTUAL POWER (BLACK LINE WITH CIRCLES) OVER THE DAY OF 2018-02-04: DAY-AHEAD FORECAST (LEFT) AND 30-MINUTE-AHEAD FORECAST (RIGHT)

The probabilistic forecasts are composed of 21 quantiles: 1%, 5% ... 95% and 99%. The wind farm actual generation has X% of probability to be below the X% quantile. The probabilistic forecasts are capable of describing all the possible futures and their likelihood and can be used as inputs for a stochastic programming approach.

2.2.1.2 PV POWER FORECASTING

PV power forecasting methods are primarily based on statistical learning between PV generation data and meteorological data. The diagram in Figure 8 represents the meteorological data used in the state of the art to obtain the best PV generation forecasts according to the prediction horizon. The longer the time horizon gets, the farther the error grows.

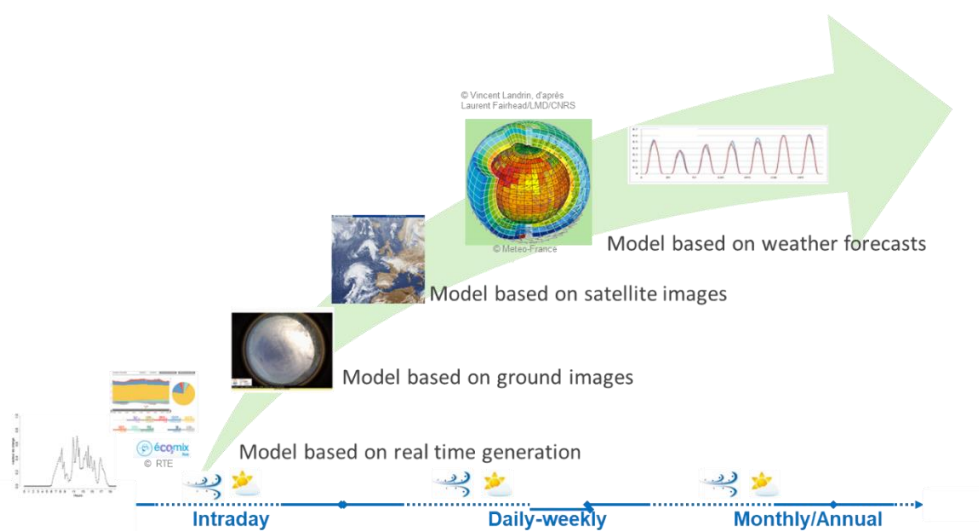


FIGURE 8. PV FORECASTING MODELS

For the time horizon considered by the VPP demonstration, intraday and daily forecasts are needed, thus, models based on real time generation are the most relevant to be applied. As for the wind generation forecasts, both deterministic and probabilistic PV forecasts are generated and used.

2.2.2 CENTRALISED OPTIMIZATION AND CONTROL – ENERGY MANAGEMENT SYSTEM (EMS)

The **centralised EMS** of the VPP is mainly composed of 2 functions: the **day-ahead and intraday optimization** and scheduling as well as the **short-term control and re-dispatch**. The outputs of the forecasting tools as well as local measurements from the controlled assets are used as inputs by the EMS for the generation of the operating programs at different time scales.

2.2.2.1 OPERATIONAL PLANNING SCHEDULER (OPS)

Located on a remote server, the operational planning scheduler provides optimal energy and multi-service schedules for the VPP every 30 minutes at most, based on the most recent forecasts and measurements available.

2.2.2.1.1 GENERAL DESCRIPTION

Each schedule defines the overall energy and the sequence of services to be provided in the coming 36 hours with a 30-minute interval. For instance, it defines the upward and downward power reserves of the BESS from 8:00 to 8:30 if it is expected to deliver the FCR service.

To define such a schedule, the scheduler uses at least the following data:

- the wind and PV generation forecasts,
- the forecasts of energy and services prices²,
- some data measured on the resources such as the state of charge of the BESS,
- a set of parameters provided by the user and related to the services and optimization algorithm considered.

The development of the OPS is based on an existing planning software, named '*Clevery*', elaborated entirely by EDF R&D. This software is developed for multi-energy systems in C++ and can be used with different commercial or open-source solvers. The software has a graphical user interface where the user can model the system of which the schedule has to be optimized. Figure 9 shows the power flows within the French VPP, as well as between the VPP and the different markets, using the user graphical interface of *Clevery* software.

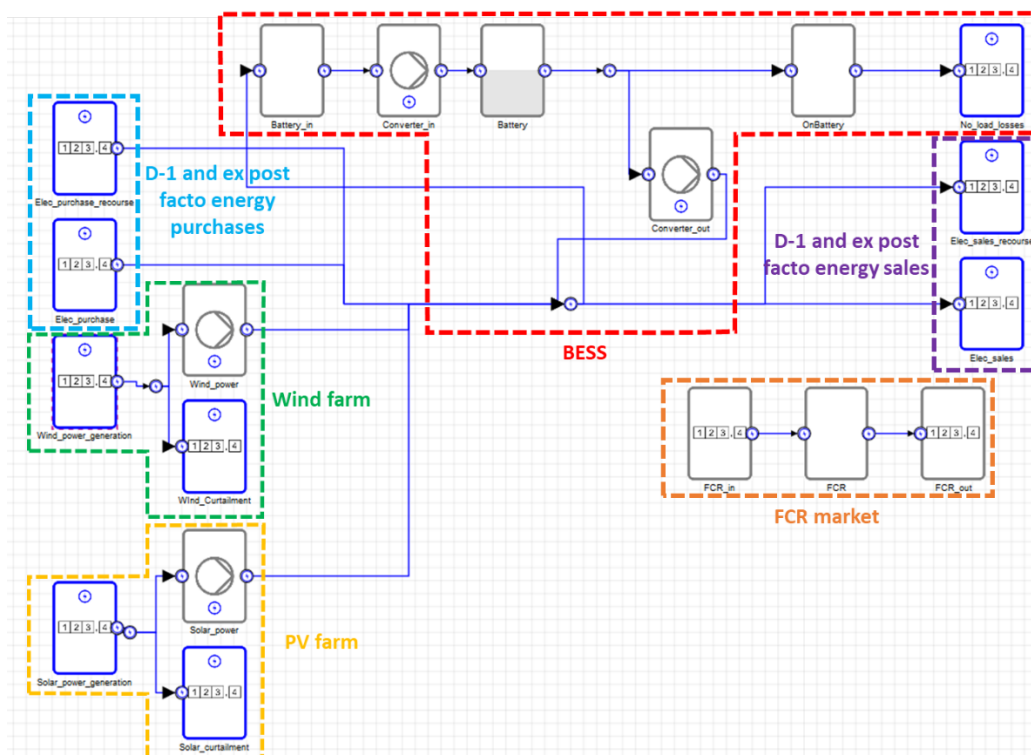


FIGURE 9. BASE MODEL OF THE VPP IN THE SCHEDULER SOFTWARE

The model includes the three resources managed by the French VPP: the 2-MW BESS, the 12-MW *Anglure 2* wind farm, and the emulated 6-MW PV farm and allows to perform services scheduling optimization. In addition to this graphical model, which gives the power flow equations to be satisfied during the optimization process, a

² Most tested services are expected to have time-varying prices, depending on supply and demand and on grid operation situations. It is therefore necessary to have the "knowledge" of the prices of different services before the real time to be able to perform day-ahead scheduling and intraday re-scheduling. In practice, forecasting of energy and services prices can be achieved according to mathematic models and to robust knowledge on historical data. However, the use of such price forecasting tools is out of scope of the present demonstration, as neither service nor energy provided by the VPP will be sold to the real related markets in France. The objective of the work is to develop tools and software of which the operation can be technically demonstrated, but not to reproduce the exact and real market integration processes under strict regulatory and economic constraints. Thus, some historical prices and simplified market assumptions have been applied throughout the demonstration work.

configuration file has been created to provide additional equations, corresponding data (prices, wind and PV generation), the period of optimization, the sampling interval size and other optimization parameters.

Some of the additional equations are related to the simplified market assumptions adopted in the French demonstration, especially:

- The gate closure time of the day-ahead markets is at 12:00, which means that the day-ahead services' schedule of the VPP has to be committed by 12:00.
- To satisfy its day-ahead commitments (e.g., overall energy produced/consumed by the VPP, and level of reserve) and/or maximize its full income, the VPP can adapt its services' schedule in an intraday basis. Regarding the energy arbitrage, intraday (or ex post facto) energy sales or purchases are indeed possible at extra costs.
- Due to its high complexity, the intraday electricity market is not considered. In other words, the VPP intends to meet its day-ahead schedule. Deviations from this schedule are valued at the positive/negative imbalance settlement prices.
- PV and wind generation benefit no longer from specific feed-in tariffs as in today's case, meaning that the VPP should sell produced energy to the French electricity energy market like conventional power plants.

2.2.2.1.2 DEVELOPMENT STATUS AND INNOVATIONS

Clevery was initially designed for optimal management of power plants and only deterministic optimization approaches were possible before EU-SysFlex project. Since the beginning of the project, much progress has been made and necessary developments have been realized, to adapt this software to the demonstration case, and thus, to be able to schedule several services provided by a portfolio of distributed resources. The following improvements are the most important among others:

- **enabling stochastic optimization** using probabilistic renewable generation scenarios,
- **modelling of the frequency containment reserve provided by multi-resources.**
- Enabling stochastic optimization

Classical deterministic optimization approaches show some limitations regarding how uncertainties like renewable generation forecast errors can be taken into account. Accordingly, *Clevery* was first improved in 2019 to enable stochastic optimization, using probabilistic PV and wind generation scenarios. These scenarios were randomly created by considering:

- quantiles of the probabilistic generation forecasts (from the statistical generation forecasting model as depicted in Section 2.2.1), which give information on the generation probability distribution at a given time,
- historical data of copula, which describe the dependence between the generation values at different times [11].

Based on the probabilistic generation scenarios, the optimization solution adopted was to use a two-stage stochastic programming approach. The general paradigm is that a decision needs to be made prior to observing

uncertainties (first-stage decision), while another can be made after uncertainties have been revealed (second-stage or recourse decision). The optimal policy from such a model is a single first-stage policy and a collection of recourse decisions that define which second-stage action should be taken in response to each uncertain outcome. In the case of the operational planning scheduler:

- the first-stage decision is the VPP's commitment to the day-ahead markets, i.e., the day-ahead energy sales/purchases and the amount of FCR. The commitment of the VPP is common to all the scenarios.
- the recourse decisions are the flexibilities of the VPP used to compensate for generation forecast errors, i.e., the BESS power, the curtailed renewable energy and/or the intraday (or ex post facto) energy sales/purchases. The recourse decision is specific to the scenario considered.

Detailed simulation results and economic assessment, which proved the value of considering probabilistic generation forecasts and stochastic optimization for EMS development, will be presented in Chapter 3 of the present report.

- Modelling of FCR provision

The pre-existing version of *Clevery* could only perform energy arbitrage considering optimal power and energy management of different resources. For the purpose of the EU-SysFlex demonstration, the software was then updated in 2020 by modelling the provision of frequency containment reserve³. It was assumed that the VPP should participate in the FCR market as a whole, by offering the reserves provided by both storage and wind generation. The total FCR of the VPP was modelled to be symmetrical or asymmetrical depending on user-defined parameters. The sum of the frequency reserves allocated on the BESS and on the wind farm corresponds, at all times, to the total scheduled FCR quantity. Thus, at the VPP level, the FCR program engaged on D-1 is always respected. However, the optimal FCR distribution between the two assets is not necessarily equivalent and is calculated by considering the overall optimization of the use of the assets as well as their availabilities. This distribution can also be systematically updated following intraday rescheduling.

The wind FCR was modelled in the way that the constitution of upward reserve would lead to curtailment of wind power, whereas the generation of the wind farm would not change while providing downward reserve. In the latter case, the activation of downward FCR will reduce the VPP's energy sales in the energy market, compared to the originally planned quantity. Nevertheless, the impact is quite limited, as the energy dedicated to FCR should only be a small part of the total wind generation in practice and this sale loss could be in part financially compensated when FCR is provided by the VPP.

³ Note that FRR (frequency restoration reserve) provision is not modelled in the OPS for two main reasons:

- First, the current market rules of FRR for the participation of BESS are not yet as clear as that of FCR. The anticipation of future market rules is out of scope of the present demonstration.
- Second, the French VPP is not sufficiently nor optimally sized to participate continuously in FRR, therefore only technical feasibility of the FRR provision by storage and by wind generation have been demonstrated under real grid conditions by performing experimental tests over a relatively short period.

Consequently, there is no need to model the FRR provision in the OPS for the VPP management. However, technically this can be achieved, similarly as the modelling of FCR, by considering another form of the reserved capacity (size, duration, commitment rules, ...).

Seen from the OPS, the volume of FCR that can be allocated on the wind farm depends strongly on the wind generation forecasts, which is the absolute maximum power level considered in the scheduling process. In addition to the stochasticity, some further rules have been added to model the FCR allocation on the wind farm:

- The maximum level of FCR that can be provided is limited to a percentage of the forecasted wind power. This percentage value can be defined by the user according to the requirement of System Operators (SO) and to the technical capability of the wind farm considered.
- The wind farm can participate in the FCR market (i.e. the allocation of reserve is enabled) only if the forecasted wind power is higher than a certain minimum value (e.g.: 500 kW).

Some simulation and experimental results will be given later in the present report in Chapter 3, to illustrate how the FCR provision is concretely considered by the OPS.

In summary, the improved version of the OPS allows to perform services scheduling optimization in case the VPP provides simultaneously or individually:

- the energy arbitrage using all the resources, through D-1 and ex post facto energy purchases/sales,
- symmetrical or asymmetrical FCR, under consideration of the requirements of the SO.

The OPS is necessary to maximise the profitability of the VPP with respect to material, contractual and regulatory constraints: resources limits, grid issues, market closure, SO requests... Two kinds of Mixed-Integer Linear Programming (MILP) approaches are available to generate schedules: **classical approaches using deterministic generation forecasts, and two-stage stochastic approaches using random generation scenarios** (built from probabilistic forecasts and copula historical data).

2.2.2.2 SHORT-TERM CONTROL (STC)

As previously mentioned, the operational planning scheduler is run every 30 minutes at most to optimize the intraday services schedule of the VPP using the most recent renewable generation forecasts and the up-to-date SoC of the BESS. Especially, for the next 30-minute interval, the OPS calculates the amount of energy that the VPP needs to produce/consume as well as the power capacity that needs to be reserved for FCR provision.

However, because of its resolution time, the OPS cannot consider what happens within each scheduling time step and therefore does not take any follow-up action if unexpected phenomenon occur during this period. For example, the performance assessment of the FCR delivery is based on the data analyses of 10-second averaged active power responses according to the French Transmission System Operator (TSO)'s requirement [12] and could be largely impacted by fast fluctuations of the VPP generation within each 30-minute interval. Furthermore, the engaged energy and services schedules could also be sometimes hardly respected facing deviations from the forecasts, if the setpoints calculated by the OPS are strictly applied without any short-term corrective actions.

Thus, another layer of control called "Short-Term Control (STC)", which coordinates with the layer of medium- and long-term optimization, is also implemented in the EMS of the VPP to ensure its continuous and correct operation. As illustrated in Figure 10, based on the orders provided by the OPS for the ongoing 30-minute interval, which are generally constant values, the STC generates and sends more detailed setpoints every second to each resource. It will take appropriate actions within each scheduling time step to achieve, to the extent possible, the following goals: 1/ to control the SoC of the BESS according to the expected SoC reference at the end of each time step, which is predefined by the scheduler allowing to optimize the use of the storage in the next scheduling period; 2/ to guarantee, the energy engaged by the VPP in each time step to be sold in the energy market; 3/ to monitor, in accordance with the requirement of SO, the performance of the VPP in regard to the services that are being provided.

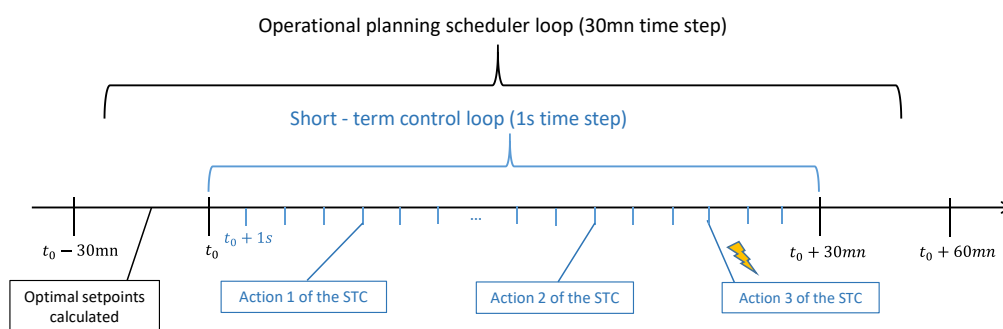


FIGURE 10. OPERATION TIMELINE OF THE SHORT-TERM CONTROL

It should be noted that some of the abovementioned goals are not mutually compatible and sometimes conflicting, as available flexibilities within each optimization loop are quite limited in such a VPP and cannot be used to manage all the unexpected deviations or events. Priorities should be established to make the most relevant decisions of STC actions according to the operating strategy of the VPP.

The layer of STC has been entirely designed and developed by EDF R&D for the EU-SysFlex demonstration. For the reason of a patent application, detailed descriptions of the advanced functions of the STC as well as the related simulation results will not be given in the present report.

2.2.3 LOCAL CONTROLLERS OF INDIVIDUAL ASSETS

The operational planning scheduler, together with the short-term control layer, constitutes the centralised EMS of the VPP, which is implemented and run on remote servers. As illustrated in Figure 11, once the power setpoints from the EMS are received, the ultimate control layer, including local controllers installed at the different sites of the resources, autonomously manages the execution of the services allocated by the EMS.

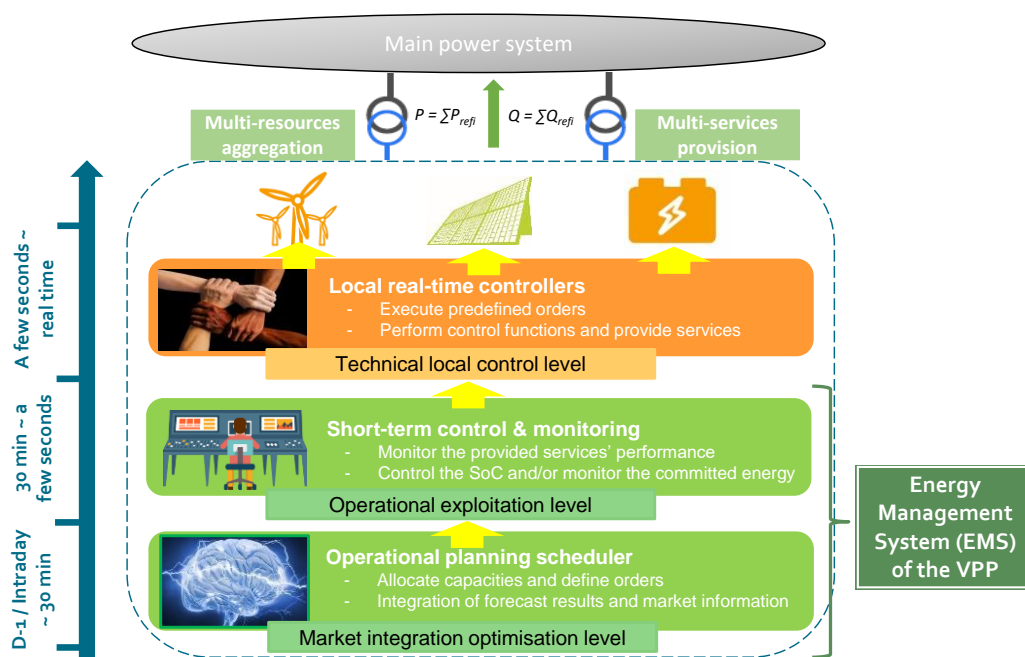


FIGURE 11. CONTROL LAYERS OF THE FRENCH DEMONSTRATION

Local controllers react in real time and are responsible for sending active and reactive power references to the controlled assets, according to local measurement such as frequency and voltage, as well as to the physical laws of the different services as specified by SO. In the French VPP, due to technical limits of the PV inverters, ancillary services cannot be provided by the PV panels and are rather allocated on the wind farm and the BESS. Therefore, dedicated wind and storage controllers have been elaborated and updated by ENERCON for the needs of the demonstration.

2.2.3.1 WIND FCU CONTROLLER

The control system of the *Anglure 2* wind farm used before EU-SysFlex was the ENERCON standard SCADA RTU controller. Its main roles were 1/to remotely monitor electrical quantities such as voltage, current, active and reactive power at the PoC (Point of Connection) ; 2/to ensure a closed-loop control of the maximum injected active and reactive power as per limited or requested by the SO. The RTU is inadequate for the provision of the enhanced wind services that need to be demonstrated in the French VPP as its typical response time is approximately 30 seconds.

Therefore, the RTU was replaced by a more advanced controller – the ENERCON FCU E2, which was successfully installed at the *Anglure* wind farm site in 2019 and fully commissioned in early 2020. One can refer to the previous WP8 report [3] for more details regarding the on-site installation and controller update work.

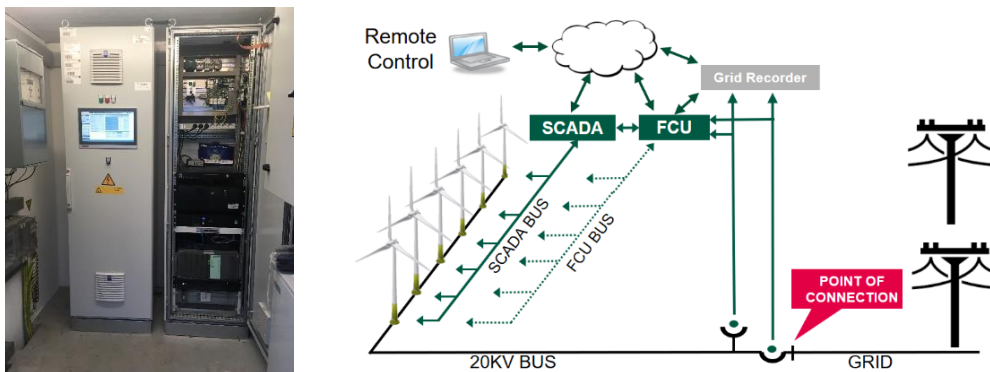


FIGURE 12. FCU E2 CONTROLLER: CONTROL CABINET (LEFT); ANGLURE WIND FARM STRUCTURE (RIGHT)

The FCU system consists of central hardware and software components close to the network connection point, additional hardware in each wind turbine, and a dedicated data bus connection to be installed separately using fibre-optic cables between wind turbines and the FCU (Figure 12). The ability of the FCU to communicate directly with individual wind turbines through fibre-optic cables is essential for achieving the desired fast control properties.

The control algorithms implemented in the FCU can be used to control the active power infeed as well as the reactive power, the voltage, or the power factor at the coupling point. Setpoints can either be fixed parameters or transmitted online via an appropriate interface. For the EU-SysFlex demonstration of frequency services, active power controllers are used, whereas reactive power controllers have not been tested even if they are technically available. Indeed, *Anglure 2* is connected to the French distribution grid via a dedicated feeder with an agreed reactive power injection plan with the DSO. Reactive power management is therefore not possible during the experiments.

Different control strategies were implemented for offering the active power – frequency services:

- Regarding the very fast service, such as FFR, the control strategy of wind inertia-based FFR allows the wind farm to provide under-frequency response within 0.5-2 seconds, but with limited magnitude and duration of the order of 5-10% of rated power over 10-15 seconds.
- In terms of FCR service, the control function was designed by carefully considering the compliance with the requirements specified in the European network code 'Requirement for Generators' (RfG) [13]. Furthermore, the separation between the positive FCR (i.e. increasing active power in case of under-frequency) and negative FCR (i.e. decreasing active power in case of over-frequency) has also been implemented. In fact, renewable generation such as wind and PV are more suitable to provide only negative FCR for economic reasons (as positive FCR requires generation curtailment, leading to a loss of primary energy), while positive FCR can be offered by other assets of a VPP such as the BESS, in order to keep the symmetry of the FCR product as requested by the current market rules.
- For FRR provision, the controller does not react to the frequency changes but regulates the active power infeed at the connection point according to the time-dependent signal sent by the TSO in practice (which is the 'level N' in France [12]), and by the EMS in the demonstration case.

In addition, multi-services provision is allowed by the FCU, meaning that all the three active power services can be simultaneously offered to the power system if it is decided by the EMS to do so.

2.2.3.2 STORAGE E-SCU CONTROLLER

The E-SCU (E-Storage Control Unit) is the superordinate controller that determines the power that should be set in the BCS (Battery Control System) to charge or discharge the energy storage system. By using external setpoints, and as well by using local grid frequency measurement, the E-SCU activates the requested services through the BCS. The external setpoints can be emitted to the E-SCU either by EMS of the VPP, or by the control room in Concept Grid as priority signals. The E-SCU uses the voltage and current measurements at the point of connection of the BESS in order to evaluate electrical values such as active and reactive power, frequency, etc.

Moreover, as real frequency events are not 'controllable' and significant incidents triggering some services can be rare and hardly predictable, the E-SCU can as well receive a fake frequency signal allowing for 'forcing' the activation of certain frequency-dependent services.

Several operational modes of E-SCU had been developed in 2019 and were validated through the local tests performed in 2020:

- Manual mode: this mode allows the operation of the battery with user-defined power setpoints. This enables the user, for example, to drive manually the battery to a desired SoC. When this is used, all other services are inhibited.
- FCR service: in case of frequency deviations, the E-SCU can contribute to stabilize the grid frequency around the reference frequency by injecting/absorbing some active power proportionally to the frequency deviation.
- FFR service: as for FCR, FFR responds to frequency deviation but in a much faster way (~1 s versus ~30 s).
- aFRR service: the automatic FRR service orders the storage system to produce an active power setpoint upon request of the TSO.
- Ramp Rate Control (RRC): this mode allows for the reduction of the active power variations of renewable resources within the VPP (limitation of dP/dt).

Depending on the active mode, different logics are used by the E-SCU to calculate the power setpoints. It is noteworthy that, as a BESS system can react very fast (in the order of 250 ms), a special parameter T_r (time constant) is used for each mode in order to adapt the response time of the system.

2.2.4 HUMAN-MACHINE INTERFACE

To be able to perform experimental tests of the French demonstration in a remote but safe manner, a dedicated HMI programmed in Python has been developed to monitor, control and supervise the VPP. The application is split in 4 tabs:

- On the first two pages of the HMI (Figure 13), the operational state as well as main electrical values of the wind farm and the storage can be respectively visualized, based on live measurement transmitted from

each site. The graph zone to the right offers the ability to show historical data through interactive graphs and to perform basic comparisons. More complex analyses could be performed with ad-hoc tools, based on a post-treatment extraction of the database. The configuration zone to the left is used to get configuration parameters (mainly for the provision of different services) of running assets, and to modify them in case of necessity.

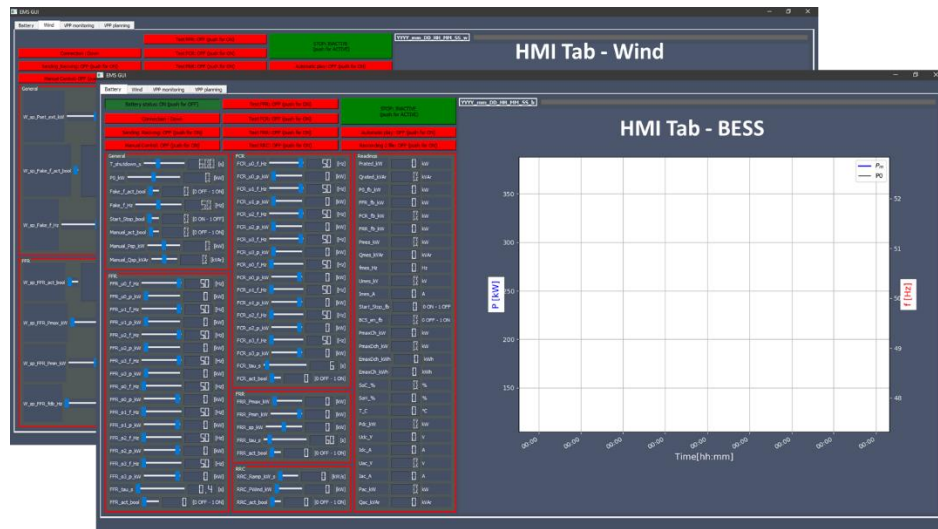


FIGURE 13. HMI PAGES FOR CONTROL AND SUPERVISION

- On the two last pages of the HMI (Figure 14), the overall state and important electrical values seen at the VPP level can be visualized, such as the active power infeed of each asset (including PV generation) and the power references, the measured and targeted state of charge of the battery, the instant effective frequency reserves provided by the whole VPP, etc. The information such as energy and reserve prices as well as day-ahead forecasts, which help to understand the power and services schedules received from the EMS, are also displayed.

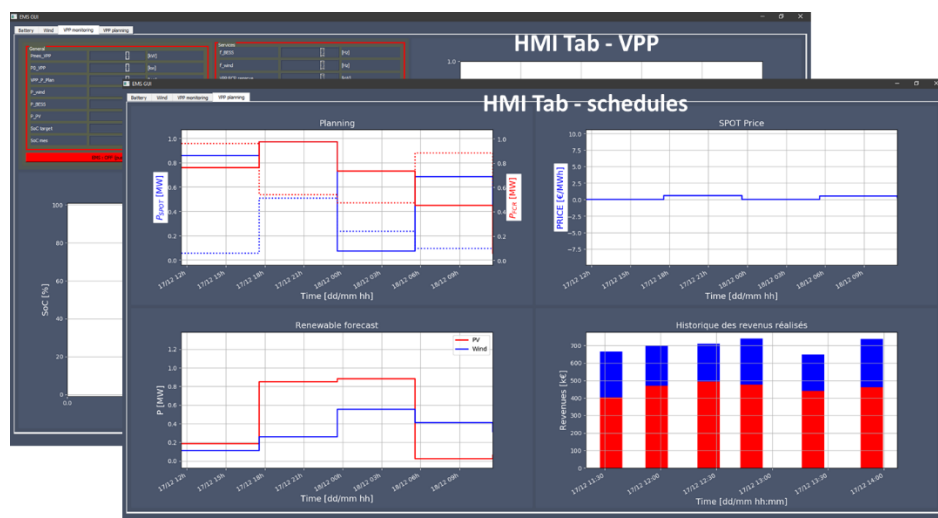


FIGURE 14. HMI PAGES FOR VPP MONITORING

The developed HMI has been proved useful and efficient for the full-chain VPP operation experimental tests performed in 2021, as it not only allows a visual supervision of the general state of each asset, but also enables remote control parameters setting during experimentations.

2.3 IMPLEMENTATION OF THE COMMUNICATION INFRASTRUCTURE

Besides hardware and software components, the communication architecture is another important aspect in the VPP's operation to ensure data exchanges within different control layers and assets. To participate in the proposed services, fast and accurate communication solutions must be adopted – **an IEC 61850-based and hardware-agnostic platform** developed by EDF R&D is used in the French demonstration. This platform presents several advantages, such as the **flexibility to manage the software, firmware and configurations** on remote devices (e.g.: Intelligent Electronic Devices (IED) or grid edge devices (GED)) with an **increased level of cybersecurity**. Another important aspect is the **evolutivity** of the proposed platform since the evolutions of its software and hardware are mostly independent. This aspect allows to enhance the management of an increasing number of devices being deployed on the field for automation and of Distributed Energy Resources (DER) on all voltage levels. Furthermore, the developed software and platform are based on IEC core standards, which ensures the **interoperability and replicability** of the demonstrated solutions.

2.3.1 COMMUNICATION ARCHITECTURE

The overall communication architecture of the demonstration was first specified in 2018 [2], then adapted in 2019 to better consider the hardware constraints and demonstration needs [3]. As shown in Figure 15, the proposed architecture intended to represent a real and global environment that can be used by a larger industrial-scale VPP to manage several resources.

Grid Edge Devices (GED) are introduced to assure the communication between each DER and the VPP's EMS. GED-W stands for the device dedicated to communicating with the wind farm controller FCU; GED-S with the storage controller E-SCU and GED-P with PV inverters. This solution allows the interaction with a wide range of DER using different protocols with advanced functions integrated, such as sending measurements, receiving control signals, managing alarms, storing information locally for a short period in case of communication losses, local management intelligence, etc.

In the present demonstration, between the GEDs and the ENERCON assets' controllers (FCU and E-SCU), the communication is made using IEC 60870-5-104. The communication with the PV inverters is performed using Modbus protocol. Between the GEDs and the EMS, IEC 61850/MMS has been chosen. This protocol is richer than IEC 60870-5-104 or Modbus and is well-known on grid installations.

To guarantee the expected performance of the EMS, it is necessary to communicate with two other servers to obtain respectively the updated generation forecasts (wind and PV) and the operating programs calculated by the operational planning scheduler. Those servers are also used for other EDF projects, therefore, have to stay connected to EDF network. File transfer with the EMS is based on ODBC and SFTP.

The interactions with the markets are not the core subjects of the present demonstration, therefore, the markets considered are only 'emulated' by applying historical prices.

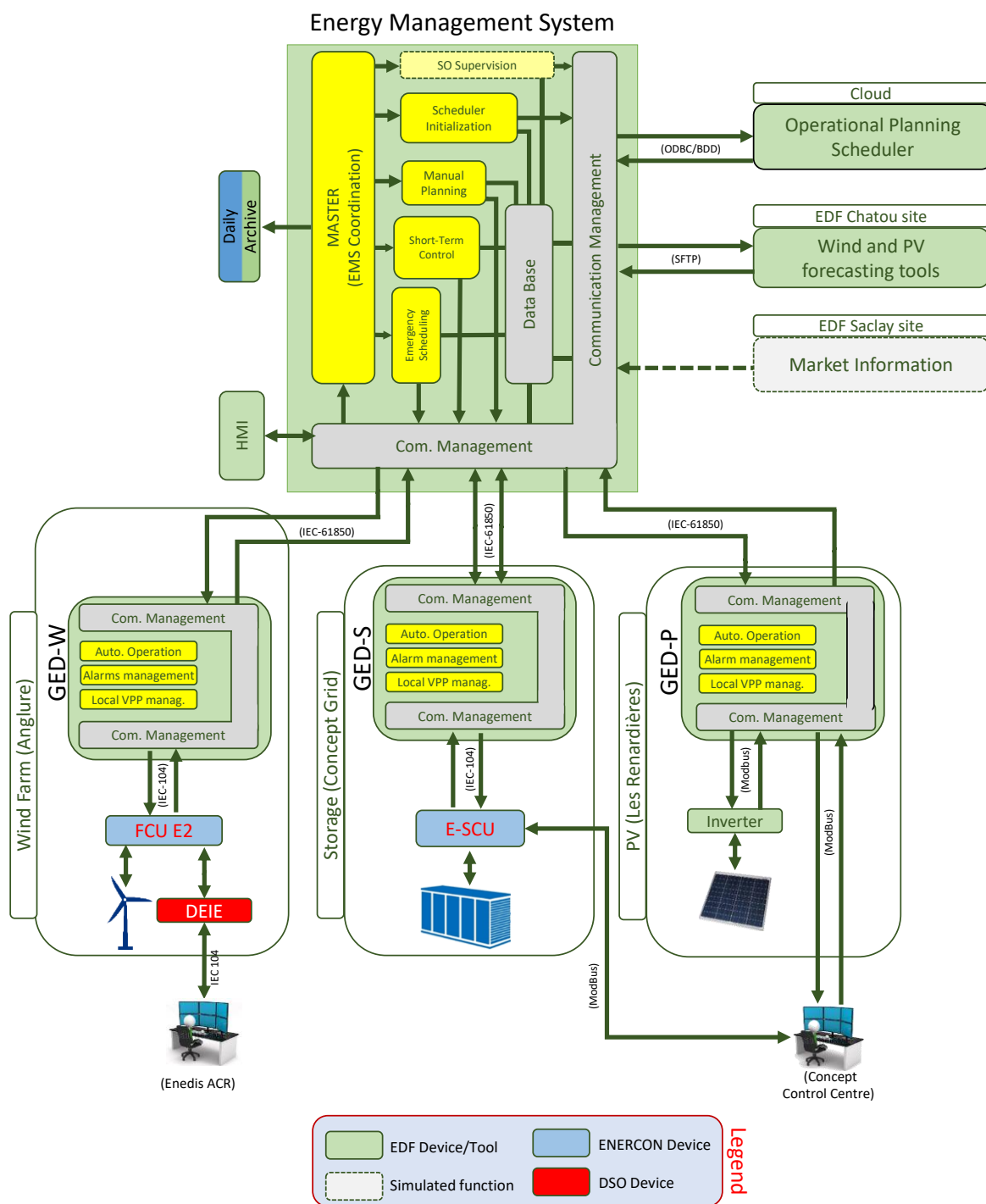


FIGURE 15. COMMUNICATION ARCHITECTURE OF WP8 DEMONSTRATION

In addition, as previously mentioned, on the BESS side, a Modbus communication channel between the CG control centre and the local controller E-SCU has been established. For security reasons, the orders given by this channel, which could represent local distribution grid operation constraints, have priority compared with that

from the VPP's EMS for services allocation or activation. On the wind farm side, the orders sent by ENEDIS through the DEIE device preinstalled in the wind farm directly operate the circuit breaker of the evacuation substation or limit wind generation output, without passing through the VPP's EMS, i.e. they are also considered as priority orders in the VPP management.

2.3.2 IT INTERFACES AND SOLUTIONS

One of the main challenges in the proposed architecture is to assure the cyber-security in all equipment and sites (three EDF laboratories at Saclay, Chatou, Les Renardères, *Anglure 2* wind farm, etc.). Each site is a confident zone that is interconnected by public Internet, which is a less confident zone. Therefore, data passing through Internet need to be secured (guarantee of confidentiality and integrity). In addition, a gatekeeper can be installed to control the boundary between "trust" and "untrust" zone.

The technical approach for the gatekeeper is installing a firewall allowing only white list IP addresses (and with the authorized protocol identified by the TCP/UDP port number). Regarding data protection, it is suggested to use a Virtual Private Network (VPN), based on IPSec technology. The encryption will prevent from data confidentiality and integrity violation as long as the encryption key of each site is kept secret. GEDs are embedded with firewalls and support IPSec if third-party hardware is not available (all data flow must pass through the GED to go to/back Internet) or the gateway to Internet does not have secured functions. The global IT architecture of the demonstration is presented in Figure 16.

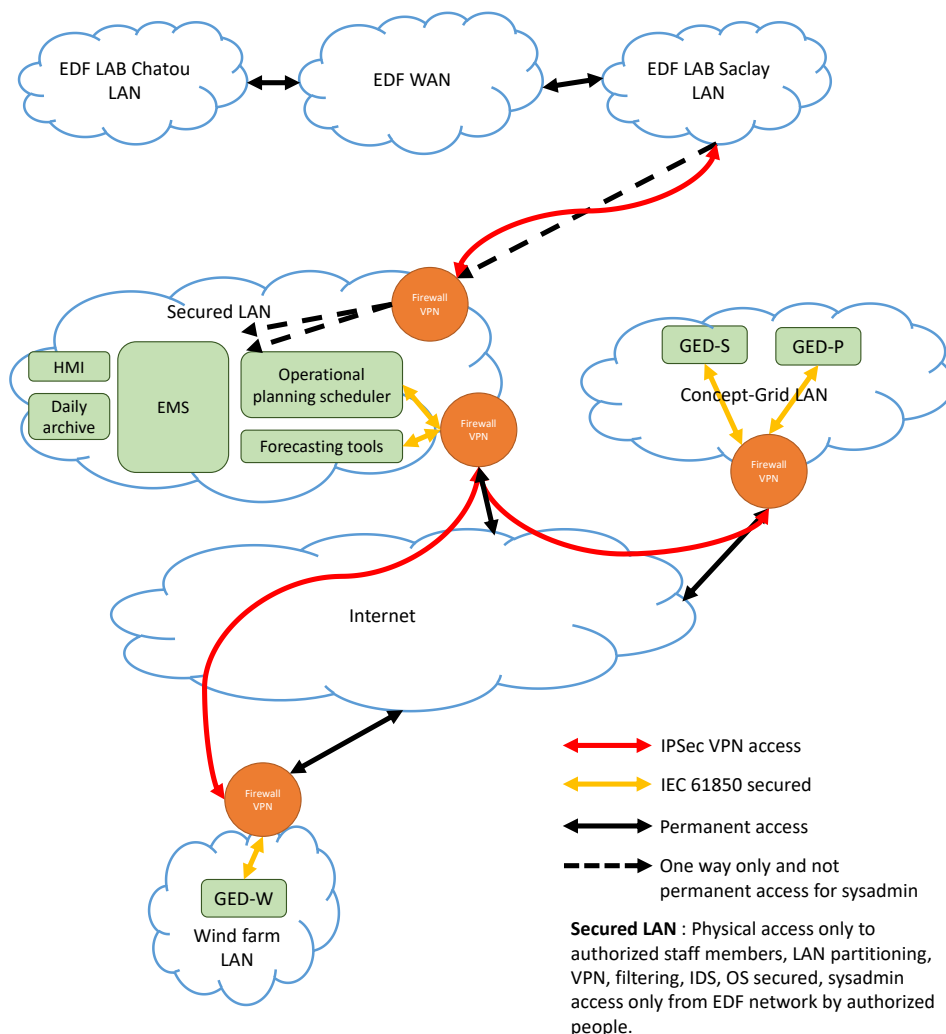


FIGURE 16: DEMONSTRATION IT ARCHITECTURE

The used servers have been installed in a datacenter, directly connected to the Internet. EDF network filters communication between internal network and the Internet. Industrial protocols are not allowed to pass from one network to the other. For this reason, the EMS was chosen to be put on a cloud (Internet). Servers are cyber-secured, and the EMS is only accessible by pre-defined IP addresses and through filtered ports. All communications carrying the assets measurement or control signals use an encrypted protocol while transiting on the Internet. Therefore, IPSec tunnels have been established from the wind farm to the EMS, so as from Concept-Grid to the EMS.

The use of VPN tunnels was not only motivated by the need to secure the connection between field assets and the cloud where the EMS is located, but also due to the fact that the MMS industrial protocol (between the GED and the EMS) does not support encryption natively. Indeed, MMS packets are not encrypted, and the encryption functionality is defined in the IEC 62351 standard. This cybersecurity layer is therefore not included inside the GEDs, whereas the encapsulation in an IPSec VPN brings the same level of security as the solution suggested in IEC 62351.

2.3.3 COMMUNICATION INFRASTRUCTURE CONFIGURATIONS

2.3.3.1 IEC 61850 STANDARD MODELLING

The GED communications and modelling layers are based on the IEC 61850 international standard as explained previously. The IEC 61850 standard describes communication services and data mediatization structure for the control-command of electrical grid systems implemented in Intelligent Electronic Devices (IED). Initially intended for substations with the publication of the IEC 61850 edition 1 in 2004, the standard is subsequently extended to equipment outside substation since the IEC 61850 edition 2 in 2011. This version upgrade now also encompasses Distributed Energy Resources (DER) assets used for the management and control of wind and solar farms, battery bench or load bank.

The general scope of the standard is to provide a set of services and data model to support information exchange between two or more IEDs from different vendors. This interoperability is achieved thanks to a common data model which describes all functions of an electric system at all levels of an installation in an object-oriented way.

As illustrated in Figure 17, specific functions are modelled into Logical Nodes (LN) and are used as basic "class" to build a full Logical Device (LD). LDs are therefore composed of the relevant LNs so as to provide the information needed for a particular device. The LNs are themselves composed of a set of predefined grouping of Data Objects (DO) of which the meaning and type are framed by the standard. The last level of modelling is the Data Attribute (DA) which contains the data to be read or set. DAs are instantiations of multiple Common Attributes (CA) such as the timestamps, the quality or magnitude using standard data types (Boolean, integer, floating point, etc.) and grouped under Common Data Classes (CDC). CDCs can be defined as the type or format of DOs.

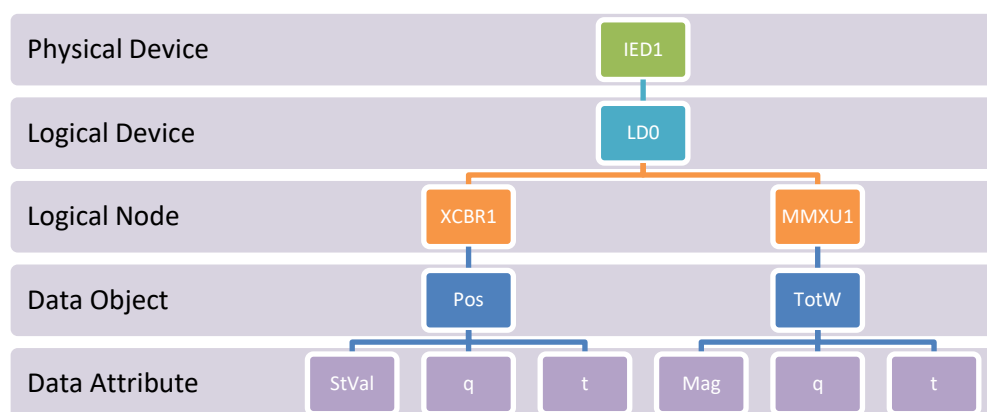


FIGURE 17. IEC 61850 MODELING STRUCTURE EXAMPLE

Access to the data from the IEC 61850 model is performed by Abstract Communication Service Interface (ACSI) services mapped to industrial protocols such as MMS, IEC 60870-5-104, Modbus, OPC DA, etc. This mapping can also be done with non-industrial protocols such as MQTT, Kinesis (AWS), Kafka or HTTP/REST. ACSI services not being dependent to a specific communication protocol, makes the IEC 61850 standard highly future-proof. DA to

be accessed by ACSI services are referenced by a functional constrained data attribute (FCDA) whose semantics and terminology are fixed by the standard.

The IEC 61850 standard thus provides a common language for data medialization and exchanges services for substations and DER assets.

2.3.3.2 INTERFACES MODELLING AND NOMENCLATURE

The implementation of the IEC 61850 standard within the GEDs is ensured by an internal software solution of EDF R&D: *GeneSys*. The solution includes a set of generic, modular and configurable libraries, that interface with each other to compose a communicative, intelligent and standardized application to meet the needs of assets in the electric utility field.

GeneSys includes several software components in order to retrieve, standardize and report data from field assets to a centralized EMS. In this context, a *GeneSys* eCore is deployed on each of the GEDs to perform the data retrieval functions as well as to send the command and setup instructions for the operational process of the DERs. The *GeneSys* eCore consists of a protocol gateway which makes it possible to interface different industrial and non-industrial protocols with the GEDs.

The first step of the IEC 61850 modelling is to best match each data of the asset which is going to be considered with a DO of the standard. In the case where a DO is not pre-defined in the standard, it is possible to define a new one by following strict terminology and semantics rules.

Once all data have been identified within the standard, modelling is done with the Substation Configuration description Language (SCL) defined by the IEC 61850 standard itself. The SCL data medialization file is based on XML format and can either be written directly or with the help of dedicated tools. The use of an SCL file editor is however strongly advised because of the complexity of the task and to avoid errors. The SCL file then goes through a validation tool that verifies the conformity of syntaxes with the requirements of the standard.

2.3.3.3 INTERFACES MAPPING

The *GeneSys* eCore needs a configuration mapping file in order to match references of the target communication protocol with the FCDAs of the IEC 61850 data model. This process is not standardized and has been performed with the help of an Excel file which lists all data to be considered with their types, addresses, descriptions, access modes (read/write), etc. This file was specified collaboratively by ENERCON and EDF in the case of the GED-S and GED-W and was produced internally by EDF R&D for the GED-P.

The IEC 61850 standard provides a dictionary of predefined LNs which list functions by categories. Each data being assigned to a LN that produces or consumes the values of this DO. For example, data consisting of calculated values of current and voltage are assigned to the LN "measurement unit" which provides the DO of

"TotW" for the total power output measurement of a DER. When the needed DO is not defined by the standard, a new DO must be added to a LN according to the semantics rules of the standard.

2.3.3.4 CONFIGURATION OF GEDS AND COMMUNICATION TESTING

The configuration of a GED can be split into two parts, network interface settings and *GeneSys* eCore configuration. The first one is done by fixing the IPv4 address in the GED network interface configuration file. The IP address indicated must be configured at the firewall/router level so that it can communicate with the EMS in the cloud through the secured VPN tunnel. On the other hand, the *GeneSys* eCore configuration is written and tested before deployment within the EDF R&D laboratory. This configuration mainly consists of two files:

- IEC 61850 SCL modelling file: XML file written according to SCL language specification that describes IEC 61850 data model of an asset.
- *GeneSys* eCore configuration file: XML file for the settings of the *GeneSys* eCore parameters and the protocol mapping.

Once a GED is configured, communication tests must be performed for its qualification. The tests consisted of sending emulated setpoints and reading measurement to/from wind and storage local controllers as well as the PV inverter, using a script with the *GeneSys* eCore python API (Application Programming Interface). The performed communication tests allowed to verify that the mapping in each GED is correct for every setpoint tag and feedback tag (same scales, same positive/negative signs, same precisions, etc.), that needs to be exchanged among different equipment.

2.3.4 PREPARATION OF THE DATABASE

Before launching experimental tests, an appropriate database should be configured in order to store and archive all the necessary data for eventual postprocessing. In the present demonstration at a reduced scale, the data traffic has been managed with two SQL databases ("MariaDB"):

- One database was used to store and archive process data (wind farm and ESS measures as well as EMS commands and planning);
- The other database was used by the operational planning scheduler to get its input and write its results and thus to communicate with the short-term control layer.

These databases were used to debug the EMS's behaviour and to plot necessary graphs for results understanding and explanation. Both databases were mirrored in a secondary server for data backup in case of crashes.

It should be noted that if many DERs are aggregated in a VPP and controlled by an EMS, data management with a SQL database could present some limits. Time Series Data Bases (TSDB) such as "Apache Cassandra", which are often NoSQL based, are dedicated to managing large amount of data (for example, by dispatching data on several nodes), and allow an efficient data storage. They are therefore recommended for the concern of scalability of the demonstrated solutions.

3. OFFLINE SIMULATION TESTING AND ASSESSMENT OF ECONOMIC KEY PERFORMANCE INDICATORS

The offline simulation tests consist in simulating precisely the behaviour of the whole VPP system, including the centralised EMS and the local assets, in real or almost real conditions, from one day to several months. It is essential to perform offline simulation testing before carrying out the experiments of full-chain VPP demonstration, in order to make sure that core optimization and control algorithms as well as interactions among different software and control modules work correctly. Furthermore, the evaluation of the global economic performance of the VPP requires running the demonstration over weeks or even months, which could be costly and time-consuming. The application of offline simulation testing in this case could be a good compromise – trends can be clearly seen and several economic Key Performance Indicators (KPIs) can be assessed while saving costs and time.

3.1 ADVANCED OFFLINE SIMULATION PLATFORM FOR VPP OPERATION

The different hardware and software components of the VPP are closely interlinked⁴ and should not be considered separately for the offline simulation. Thus, an advanced and complete VPP simulation platform has been proposed for intensive offline tests of the French demonstration. This platform was built by EDF R&D, based on software modules developed by EDF and black-box models of the wind farm and the BESS provided by ENERCON.

Basically, it simulates the dynamic behaviour of the VPP in response to the EMS commands, to the local controllers and to time series of electrical frequency and renewable generation. It is designed to capture the main interactions between the EMS/VPP components and to check whether the whole system behaves as expected in all possible situations.

3.1.1 STRUCTURE OF THE PLATFORM

As shown in Figure 18, the platform is mainly composed of three components:

- The first main component is the operational planning scheduler and its main functionalities are described in Section 2.2.2.1. Note that this OPS tested through the platform can be directly used for the WP8 demonstration without any specific adaptations.
- The second main component of the platform is a Simulink® model of the VPP and the other control layers. It includes the Short-Term Control (STC), the resources of the VPP –the wind farm, the PV panels and the BESS– and their local controllers.
- Finally, the third and last main component of the platform is a MATLAB® script corresponding to the “EMS core”. It simulates the VPP operation over a certain period with a 1-second interval, by making the OPS and the Simulink® model work together.

⁴ For example, the state of charge of the BESS at a given time depends on the control strategy, the multi-service schedule, and field measurements. Conversely, the schedule of the BESS has to be regularly updated based on the most recent measure of SoC. Therefore, optimizing each component of the EMS separately, without considering the interactions with local resources or within EMS layers, may lead to unexpected or even undesirable behaviour of the whole system.

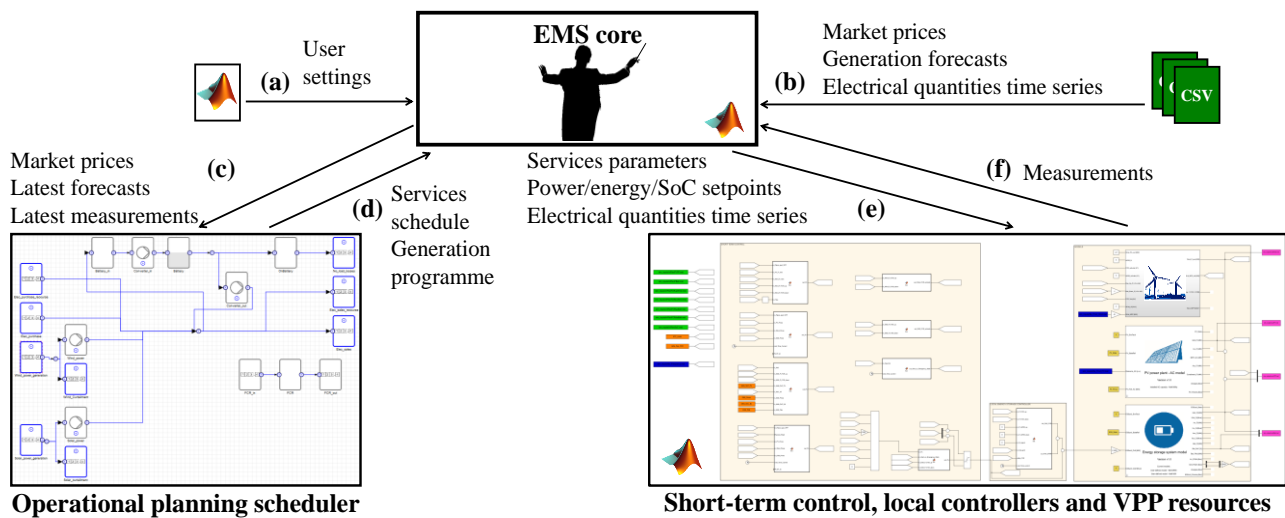


FIGURE 18. OFFLINE SIMULATION PLATFORM TO TEST THE FRENCH VPP

To speed up simulations, some components of the VPP, which are not deemed critical for the offline testing, are not modelled in detail. For instance, to represent the communication architecture, only the communication delay between components is modelled in the Simulink® model. Likewise, instead of coupling to the generation forecasting tool, only historical forecasts and generation data stored in .csv files are used for simulation objectives.

3.1.2 SIMULATION PROCESS

The following data are required to run the platform:

- VPP features, e.g., the power/energy capacity and maximum services allocation for each resource,
- EMS settings, e.g., the programming approach used by the OPS, the STC mode and the duration between two intraday schedules,
- Time series data for the OPS (with a 30-minute interval for instance): services prices forecasts (assumed to be perfect), and day-ahead and intraday PV/wind power forecasts,
- Time series data for the Simulink® model (with a 1-second interval for instance): at least PV/wind actual generation and electrical frequency.

The EMS core simulates the operation of the VPP over the duration of a studied scenario by performing the following tasks:

- 1) Load and process the user settings (see (a) in Figure 18) and the time series data (see (b) in Figure 18).
- 2) Write the services prices and the most recent forecasts and measurements available in the database of the OPS (see (c) in Figure 18).
- 3) Run the OPS to generate the day-ahead or intraday generation programme and services schedule for the VPP in the next 36 hours with a 30-minute interval.
- 4) Read the OPS outputs from its database (see (d) in Figure 18).
- 5) Process the OPS outputs to set/update the inputs for the Simulink® model (see (e) in Figure 18).

- 6) Run the Simulink® model for the period between two intraday schedules (e.g., for the next 30 minutes) to obtain the 1-second behaviour of the VPP in response to the current programme and schedule from the OPS, the STC mode adopted, and the time series.
- 7) Get and process the "measurements" from the Simulink® model, e.g., the powers of each resource and the SoC of the BESS (see (f) in Figure 18).
- 8) Repeat tasks 2 to 7 until the VPP operation is obtained for the duration of the study.

Each simulation run provides the generation programmes and services schedules from the OPS, the adjustments from the STC, the setpoints sent to the resources as well as local "measurements" simulated such as the active and reactive powers of each resource and the SoC of the BESS. From these data, different metrics are computable to analyse the performance, profitability and/or reliability of the control modules under test and to compare with other scenarios or configurations (using different programming approaches, STC modes, and/or other user settings).

3.1.3 PRACTICAL APPLICATIONS OF THE PLATFORM

The offline simulation platform has already proved useful for:

- validating the modelling assumptions made to provide energy arbitrage and FCR,
- comparing the deterministic and stochastic programming approaches used by the OPS,
- comparing different STC modes,
- studying the effects of the intraday rescheduling based on the most recent forecasts/measurements available,
- validating each release of the EMS before being implemented in the VPP demonstration,
- evaluating the technical economic performance of the VPP through long-duration simulations (e.g.: one month) for different parameter sets.

This platform precisely simulates the operation of the VPP from one day ahead to each second in real time. It has been largely employed throughout the demonstration work to jointly tune the different software parts and improve the global performance and robustness of the EMS with respect to forecast errors and contingencies. Some illustrative examples as well as the assessment results of the economic KPIs, obtained by performing simulations on the offline platform, are presented in the following sections.

3.2 DAY-AHEAD SCHEDULING AND IMPACT OF OPTIMIZATION APPROACHES

In the first instance, this section focuses on the day-ahead scheduling at the OPS level, which is the first step while operating the VPP, and show simulation results revealing the impacts of the applied approach and forecast errors on the full income of the VPP. Examples of day-ahead scheduling on a particular day are given, when applying the OPS to deterministic then probabilistic generation forecasts. Some economic figures based on simple assumptions are presented to highlight the value of performing a scenario-based stochastic optimization when renewable generation is hardly predictable, especially at a reduced scale of a few farms. Also note that in this case study, to

make the simulation results and the comparison easier to understand, it is assumed that the VPP performs only energy arbitrage and no intraday schedule updates are made.

3.2.1 DETERMINISTIC SCHEDULING USING PERFECT FORECASTS

To maximize its earnings on the day-ahead electricity market ("energy arbitrage" service), the VPP has to commit to a daily energy schedule, which is created the day before, using the most recent forecasts available. Figure 19 depicts the corresponding schedule generated by the operational planning scheduler when considering perfect forecasts for the day-ahead market prices (Figure 19(a)) and the renewable generation (dashed black line in Figure 19(b)). As expected, the OPS schedules the BESS operation so as to maximize the earnings of the VPP on the electricity market. Indeed, renewable energy is stored in the BESS when the prices are the lowest (from 4:00 to 5:00 and from 15:00 to 16:00) and reinjected when they are the highest (from 8:00 to 9:00 and from 18:00 to 19:00).

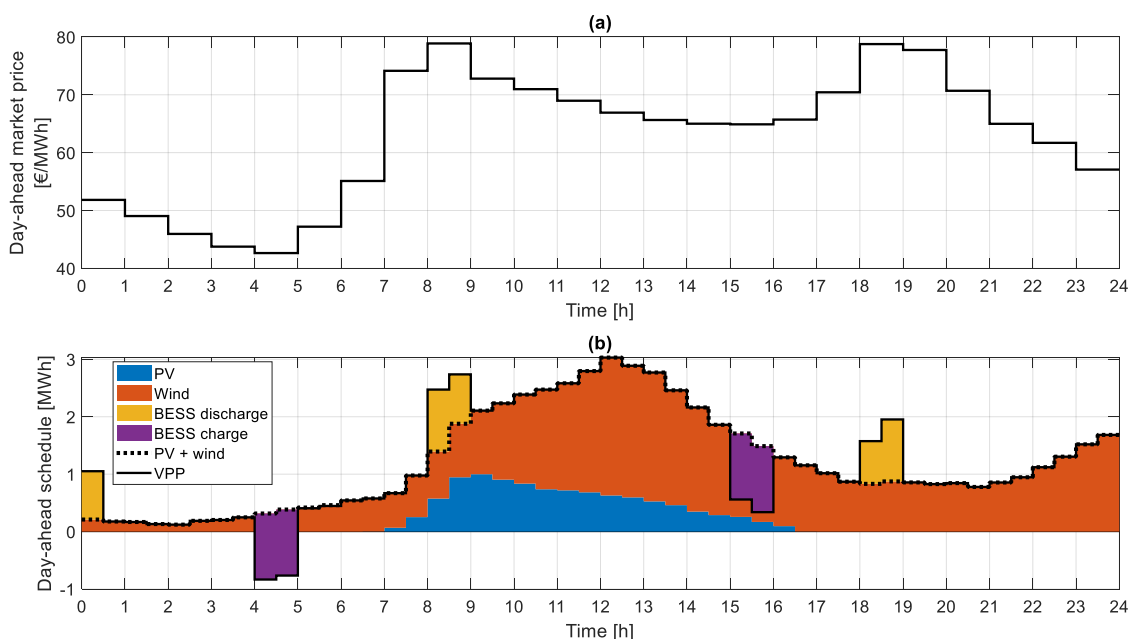


FIGURE 19. (A) DAY-AHEAD MARKET PRICE. (B) DAY-AHEAD SCHEDULE FOR ENERGY ARBITRAGE

As shown in Figure 20, the day-ahead schedule proposed for the BESS meets its power and energy capacities. For the day considered, the use of the EMS would result in an additional gain of 91 euros on the day-ahead electricity market. Note that this additional gain is dependent on the BESS size considered and is actually achieved provided there are neither forecast errors nor contingencies.

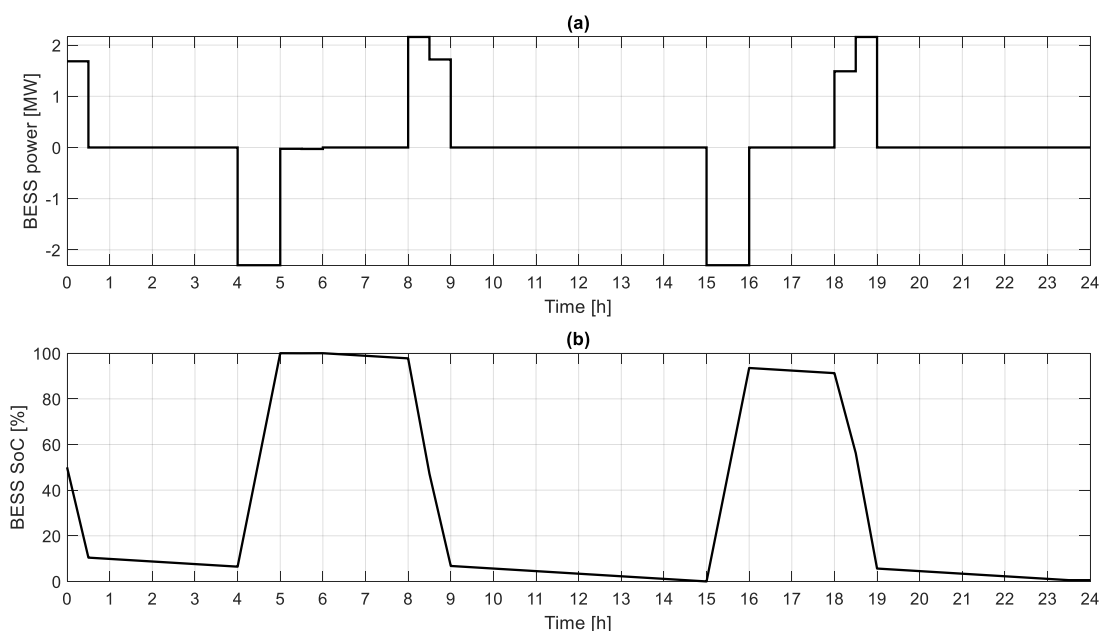


FIGURE 20. DAY-AHEAD SCHEDULE OF THE BATTERY: (A) POWER, (B) STATE OF CHARGE

3.2.2 IMPACT OF THE FORECAST ERRORS

Forecast errors may strongly impact the full income of the VPP. In particular, day-ahead generation forecasts are often inaccurate as depicted in Figure 21. This would result in significant gaps between the day-ahead schedule of the VPP and its actual injected/consumed energy.

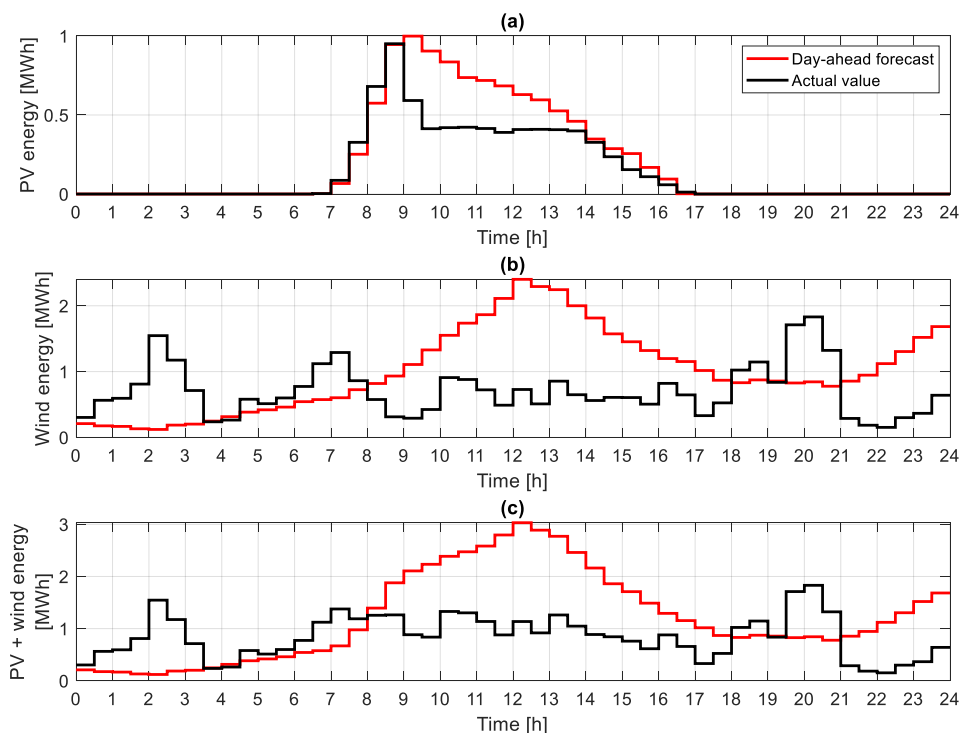


FIGURE 21. DETERMINISTIC DAY-AHEAD FORECAST AND ASSOCIATED GENERATION: (A) PV, (B) WIND, AND (C) PV + WIND⁵.

⁵ In this figure, deviations between the forecasts and the real generation of the cumulated energy in MWh are shown.

Figure 22 highlights the impact of these gaps on energy arbitrage. As the VPP does not meet its day-ahead schedule, the full income must include not only the gain on the day-ahead electricity market but also two other components:

- the loss caused by a lack of energy over any 30-minute interval (green area in Figure 22(b)),
- the gain resulting from an excess of energy (blue area in Figure 22(b)).

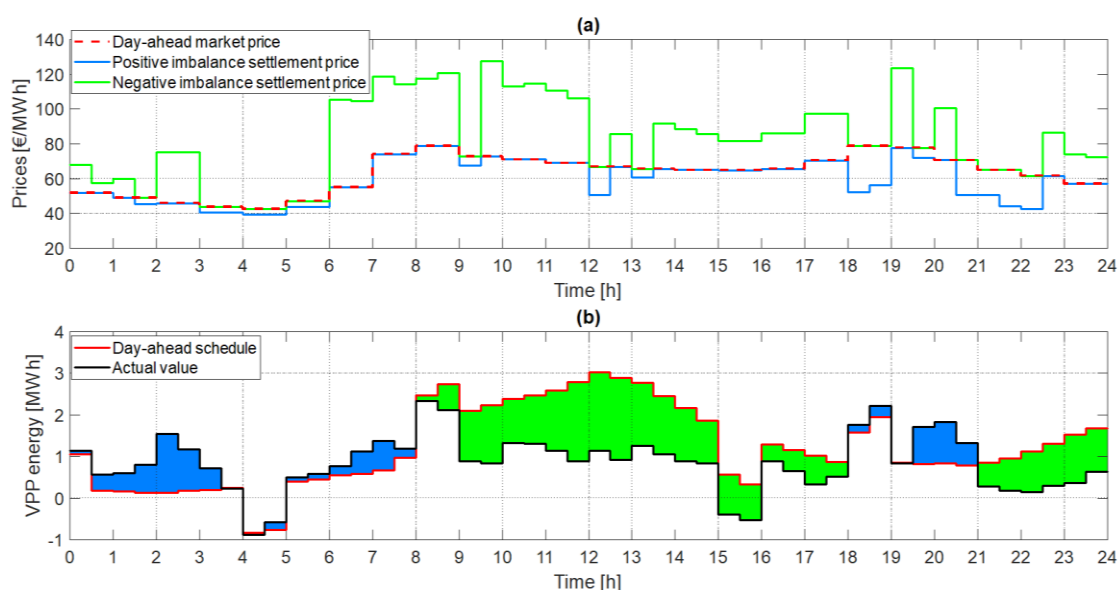


FIGURE 22. (A) PRICES OCCURING IN THE VPP FULL INCOME. (B) DAY-AHEAD SCHEDULE VERSUS ACTUAL ENERGY OF THE VPP

Note that the real full income of the VPP is necessarily lower than the theoretical maximum day-ahead income obtained from perfect forecasts, since:

- the negative imbalance settlement price is equal or higher than the day-ahead market price (Figure 22(a)),
- the positive imbalance settlement price is equal or lower than the day-ahead market price (Figure 22(a)).

For instance, the costs and benefits for the considered study case are detailed in Table 3. Not surprisingly, it turns out that the forecast errors cause a loss in earnings of 13% for this case.

	Perfect forecasts	Deterministic forecasts
Day-ahead income	+2764 €	+4036 €
Expected positive imbalance settlement gain	0 €	+524 €
Expected negative imbalance settlement loss	0 €	-2425 €
Expected full income	+2764 €	+2135 €

TABLE 3. EXPECTED COSTS AND BENEFITS WHEN PROVIDING ENERGY ARBITRAGE OVER ONE PARTICULAR DAY

3.2.3 STOCHASTIC SCHEDULING USING PROBABILISTIC FORECASTS

For the same day, instead of the deterministic approach, a stochastic scheduling based on probabilistic forecasts can also be applied. This approach is supposed to be able to better consider the uncertainties present within the VPP. Probabilistic forecasts result from the same statistical model used to build deterministic forecasts, which also include the distribution of the forecast errors over the training period. As presented previously in Section 2.2.1 and shown in Figure 23, probabilistic forecasts are composed of several quantiles (5%, ..., 95%) and the X%-quantile corresponds to the probability of the generation being less than or equal to X%.

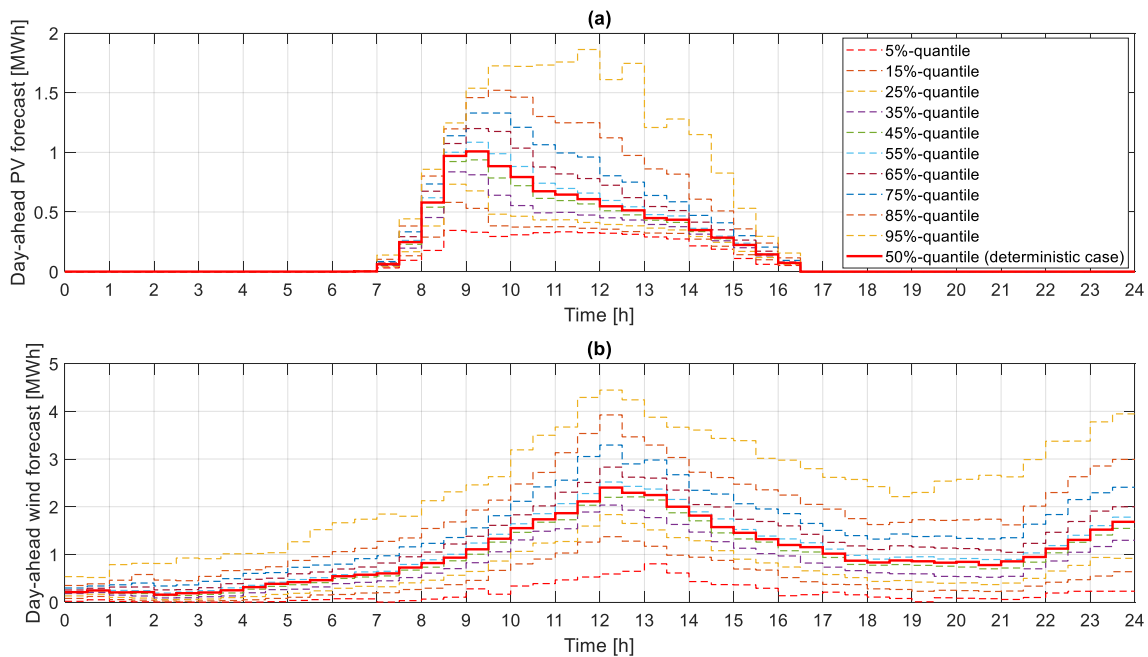


FIGURE 23. DAY-AHEAD PROBABILISTIC GENERATION FORECASTS

Using these quantiles as well as copula historical data (which describe the dependence between the generation values at different points of time), it is possible to create stochastic generation scenarios as depicted in Figure 24. The generation uncertainty can therefore be addressed in the services scheduling process using a large number of scenarios.

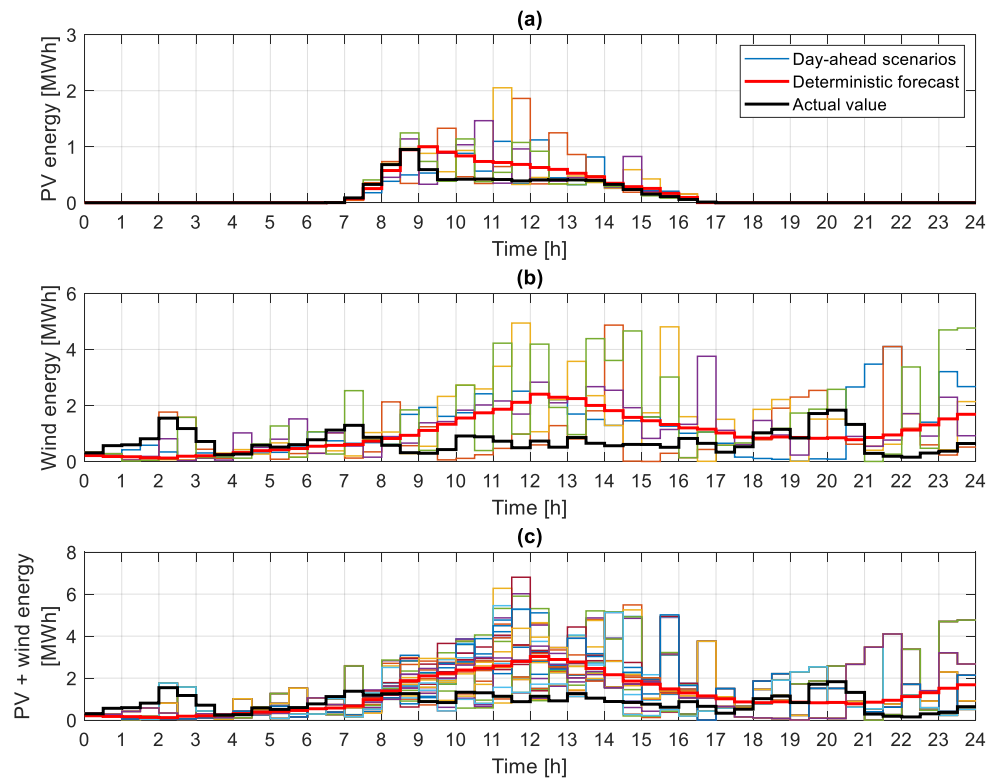


FIGURE 24. EXAMPLES OF STOCHASTIC SCENARIOS GENERATED FROM PROBABILISTIC GENERATION FORECASTS:
(A) PV, (B) WIND, (C) PV + WIND

Given these various scenarios, the OPS has to provide a unique day-ahead schedule for the VPP. The choice has been made in the optimisation process to generate a day-ahead schedule for the VPP common to all the scenarios and to fill the gap between this schedule and the renewable energy, which is specific to each scenario, by using two flexibilities: (1) the BESS charging/discharging, and (2) ex post facto energy purchases/sales on an intraday market or through the imbalance settlement mechanism. If FCR is provided by the VPP, the service schedule has to be the same for all the scenarios too.

For instance, Figure 25 shows the day-ahead results when applying the OPS to the stochastic scenarios depicted in Figure 24, in case the VPP performs energy arbitrage only:

- the potential overall energy of the VPP (colored curves in Figure 25(a)), which is composed of: (1) the day-ahead schedule to be committed (black curve in Figure 25(a)) and (2) the potential ex post facto energy purchases/sales (gaps between the black curve and the colored one in Figure 25(a));
- the potential state of charge of the BESS (colored curves in Figure 25(b)).

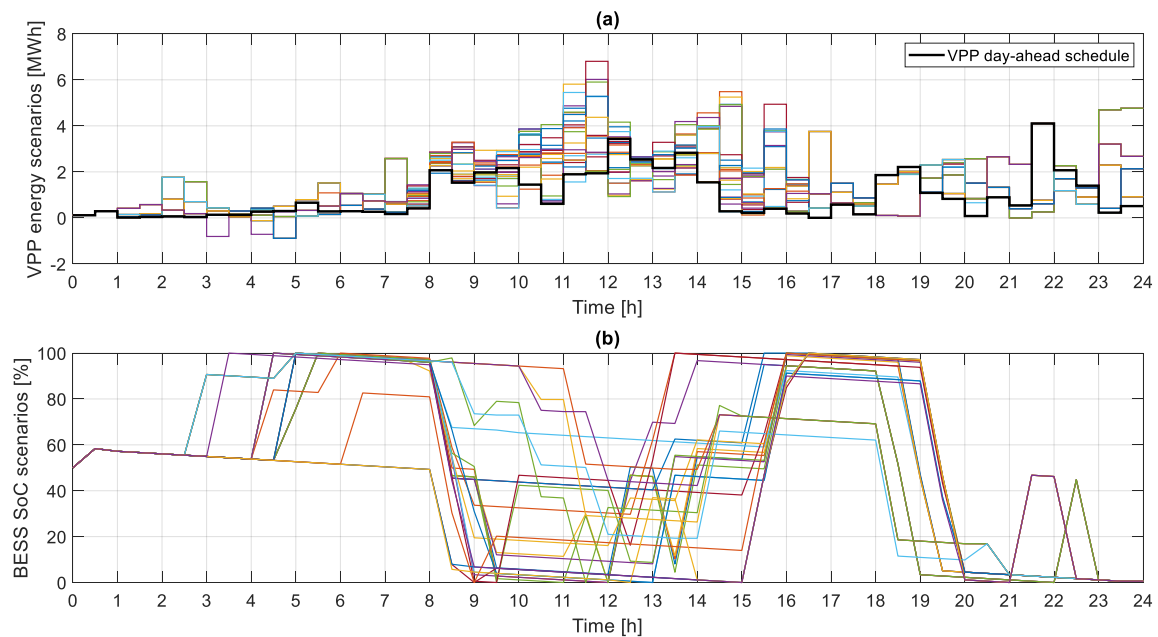


FIGURE 25. DAY-AHEAD SCHEDULE FOR ENERGY ARBITRAGE WHEN CONSIDERING PROBABILISTIC GENERATION FORECASTS:
(A) SCENARIOS OF INTRADAY ENERGY PURCHASES/SALES, (B) STATE OF CHARGE OF THE BESS

It is worth noting that:

- In most scenarios, the BESS is expected to be fully charged from 6:00 to 8:00 and from 16:00 to 18:00, which allows injecting energy to the grid when the day-ahead market prices are expected to be the highest.
- A unique day-ahead schedule for the BESS cannot be easily defined when a scenario-based stochastic optimisation of the services scheduling is considered. That is why the OPS demands the same operation of the BESS during the first hours of all the scenarios (from 0:00 to 1:00 in this example). This requirement allows for defining a short-term power/energy target to be achieved by the BESS (on an intraday basis with the STC), regardless of the generation uncertainty.

As shown in Table 4, a scenario-based stochastic optimisation of the services scheduling succeeds in increasing the full income of the VPP (+12% in average) by largely reducing the negative imbalance settlement loss for the considered study case.

	Perfect forecasts	Deterministic forecasts	Probabilistic forecasts ⁶
Day-ahead income	+2764 €	+4036 €	+3226 €
Expected positive imbalance settlement gain	0 €	+524 €	+1002 € (± 1%)
Expected negative imbalance settlement loss	0 €	-2425 €	-1827 € (± 3%)
Expected full income	+2764 €	+2135 €	+2402 € (± 2%)

TABLE 4. EXPECTED COSTS AND BENEFITS WHEN PROVIDING ENERGY ARBITRAGE OVER ONE PARTICULAR DAY, WITH PERFECT, DETERMINISTIC AND PROBABILISTIC GENERATION FORECASTS

The simulation results in this example show the interest to apply stochastic optimization by considering probabilistic generation forecasts, note however that a better daily full income is not always obtained using this approach. For instance, if the day-ahead deterministic forecasts are quite precise, the deterministic day-ahead schedule may result in lower imbalance settlement loss and thus better full income than the stochastic intraday one. Simulations over a longer duration (e.g., one month) with different variants/settings of the EMS are therefore necessary to provide more conclusive results.

3.3 ILLUSTRATION OF THE VPP OPERATION OVER A ONE-DAY SIMULATION

Once the approach for generating schedules is presented, this section gives the simulation results of the full VPP operation over an entire day, to show how the French VPP works and what kind of analysis can be carried out using the developed offline platform. The study case is based on a different scenario (day and services considered, associated market prices, etc.), which consists in positioning the VPP on the energy and FCR markets over 24 hours, using rules based on European regulation and pre-processed data from existing markets. Based on the assumptions mentioned in Section 2.2.2.1, wind and PV generation, and possibly the energy stored in the BESS, should be sold on the energy markets (no feed-in tariffs), and the VPP can provide 4-hour symmetrical FCR using the abilities of the BESS and/or the wind farm. A deterministic programming approach was applied to make the results and analysis easier to understand.

The BESS provides FCR according to the European regulation, i.e., it must maintain the maximal power reserve for 15 minutes, which amounts to maintaining the SoC between margins. The wind farm can also provide FCR, by curtailing its power from the estimated maximum available generation, as described in [14]. If needed, the BESS and the wind farm can deliver either downward or upward FCR in this VPP.

In this example, the OPS provides schedules every 4 hours, while the STC updates the 30-minute setpoints from the OPS every second using a basic strategy.

⁶ The costs and benefits displayed for the "probabilistic forecasts" case are the average values over the scenarios depicted in Figure 24. The percentage values give the range of the costs/benefits for all the considered scenarios.

3.3.1 DESIGN OF THE DAY-AHEAD SCHEDULES

Figure 26 (b) presents the schedules computed by the OPS for the VPP at noon for the next day, given several constraints (e.g., market and regulatory requirements, and simplified physical model of the BESS), the market prices (Figure 26 (a)) and the generation forecasts (red lines in Figure 27) available. These schedules are optimised to maximise the global revenues on the energy and FCR markets.

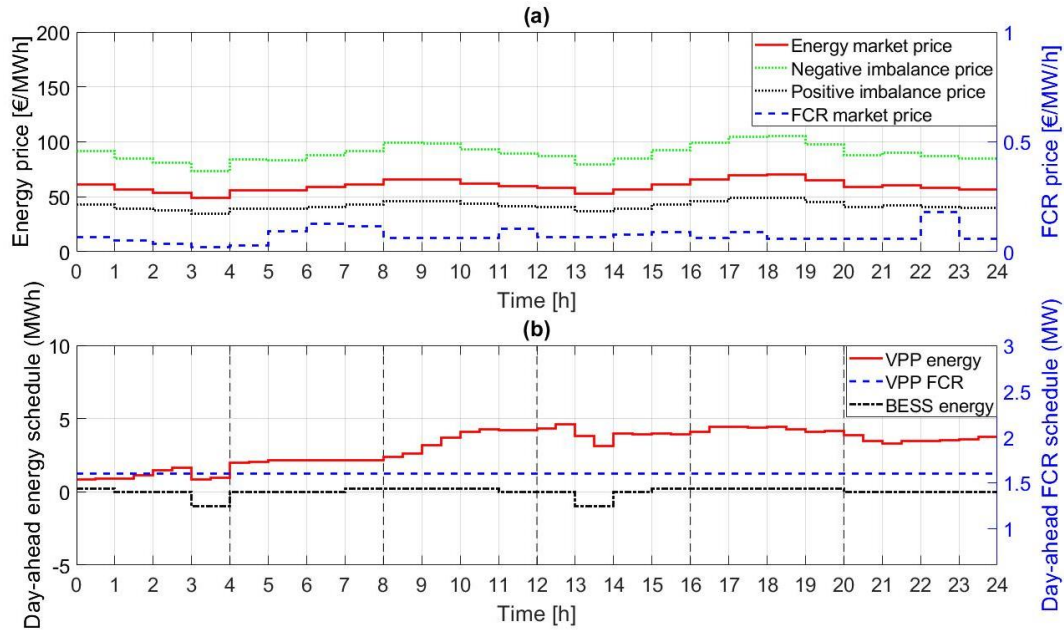


FIGURE 26. (A) MARKET PRICES AND IMBALANCE PENALTIES, (B) DAY-AHEAD SCHEDULES FOR THE VPP AND THE BESS

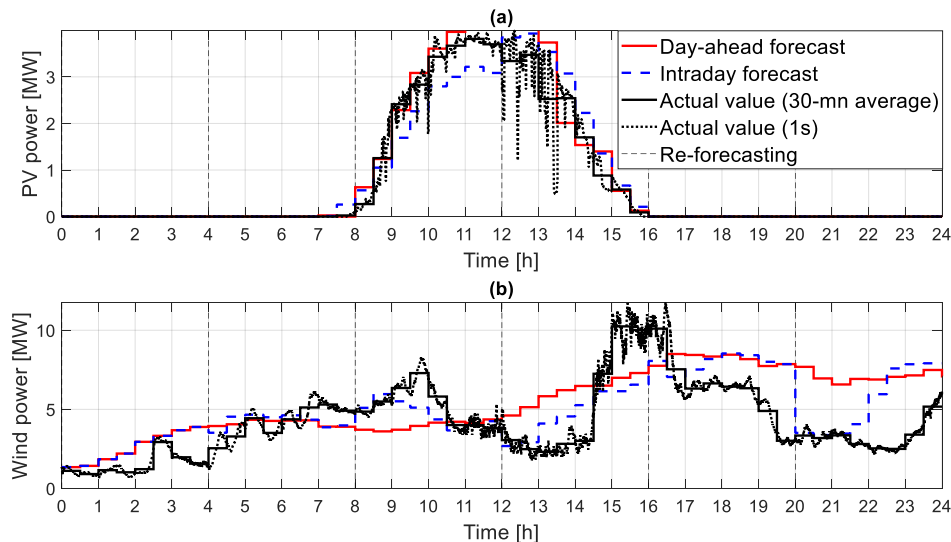


FIGURE 27. FORECASTED AND ACTUAL GENERATION: (A) PV, (B) WIND

Similarly to what has been illustrated in the previous examples, the OPS chooses to charge the BESS with the renewable energies when the energy market price is the lowest, at 3am and 1pm, and to discharge it when the price is the highest, from 7am to 11am and from 3pm to 8pm (Figure 26 (b)). Besides, the expected energy sales

from the VPP over the day is almost equal to the sum of PV and wind energy forecasts. Indeed, it is more interesting to sell energy right away than to store it and sell it later because of losses in the BESS.

In addition, the OPS plans to position the VPP in the FCR market at the maximum level for the entire day, i.e. 1.6 MW in the simulation cases⁷ (Figure 26 (b)). Indeed, FCR prices may be interesting, as it is a reserve contract and all the energy will not always be activated. Furthermore, it is beneficial all day long, as both the BESS and the wind farm can offer it and take over when the other has not enough reserve.

Note that the OPS has been successfully tested on many other study cases using the offline simulation platform.

3.3.2 SIMULATION OF THE STC OPERATION AND VPP BEHAVIOUR OVER THE FIRST 3 HOURS OF THE DAY

As described in Section 2.2.2.2, the STC adjusts the power setpoints computed by the OPS within each 30-minute interval. In this VPP, the adjustment variable is the baseline power of the BESS (P_0). A first solution consists in not modifying the P_0 computed by the OPS, i.e., P_0 is constant on each 30-minute interval (Figure 28 (a)). However, this strategy does not take into account the modelling errors made by the OPS (due to simplifications) and the SoC deviations caused by the activation of the FCR (due to frequency variations). Therefore, the BESS may not reach the SoC planned by the OPS, as shown in Figure 28 (b). Another option is thus to adjust P_0 to reach the SoC planned by the OPS for a better use of the storage in the following time steps, as shown in Figure 28 (c) – (d).

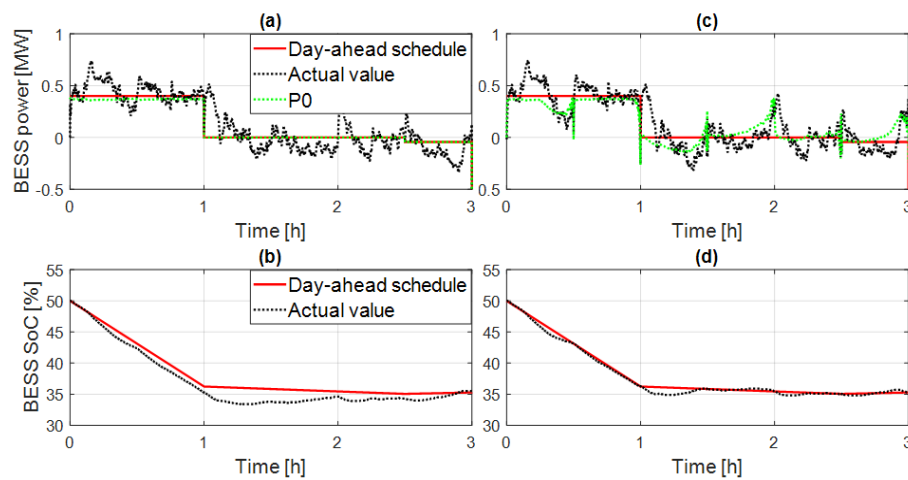


FIGURE 28. (A) (B) BESS POWER AND SOC WITH BASIC STC STRATEGY, (C) (D) BESS POWER AND SOC WITH SOC CONTROL STRATEGY

⁷ The rated power of the BESS in the French VPP is 2 MW. According to the ENTSO-E rules regarding the provision of FCR by limited energy reservoir entities such as battery storage systems [15], it is recommended to oversize the power by 25% to allow continuous FCR provision. In another word, a battery of 2-MW full capacity should not declare to provide more than 1.6 MW of FCR.

Indeed, since normal state includes a constant frequency deviation of a maximum of 49.99 mHz, the energy reservoir may be depleted. The energy reservoir management for FCR providing units or groups with limited energy reservoir takes into account this scenario in order to guarantee continuous activation of FCR. Hence, an additional power dimensioning of 25% (50 mHz divided by 200 mHz) is required to allow continuous FCR provision while applying energy reservoir management.

Note that this requirement is determined only for standalone operation of FCR providing units with limited energy reservoir and the 12-MW wind farm in the VPP has the potential to provide symmetrical or asymmetrical FCR higher than 1.6 MW when sufficient wind is available. However, to keep the symmetry of the FCR provision and for economic considerations, it is deemed in the optimization and control process that the maximum amount of FCR, which can be offered by the VPP of the size of the project, is 1.6 MW.

Among the other uncertainties occurring within the OPS time step, the actual generation of the renewables may deviate from the intraday forecast in terms of energy (Figure 27). The STC can also adjust P_0 in order to minimise these deviations within each 30-minute interval. The different strategies of the STC could be in competition among each other, and the simulation platform enables to evaluate which strategy offers the best technical and economic results on long-term simulations. In this study case, the basic strategy of the STC has been chosen for the sake of clarity.

3.3.3 GLOBAL PERFORMANCE OVER THE DAY WITH INTRADAY RESCHEDULING EVERY 4 HOURS

Thanks to the offline simulation platform, it is possible to evaluate the differences between the day-ahead and intraday schedules, both provided by the OPS. The schedules are regenerated by considering updated generation forecasts (Figure 27), the actual status of the BESS and eventual imbalance penalties for not fulfilling the day-ahead energy commitment (Figure 26 (a)). The OPS may decide to change the VPP energy schedule and/or the allocation of FCR between the wind farm and the BESS.

Figure 29 (a) highlights differences between the actual energy of the VPP and the intraday energy schedule. These discrepancies are due to variability of renewable generation. In this study case, the upward FCR is totally provided by the BESS as the provision of upward FCR by the wind farm would lead to significant curtailment. However, the downward FCR is shared between the BESS and the wind farm. This dispatch evolves with the 4-hour intraday rescheduling, as depicted in Figure 29 (b) – (c). This change is related to the evolution of the BESS SoC and to the reforecasting of renewable generation. For instance, from 7:30 to 11am, the wind farm helps the BESS to provide power and energy for FCR because the SoC value is higher than that the day-ahead schedule predicted (too high to be charged for maintaining 15 minutes of full downward FCR).

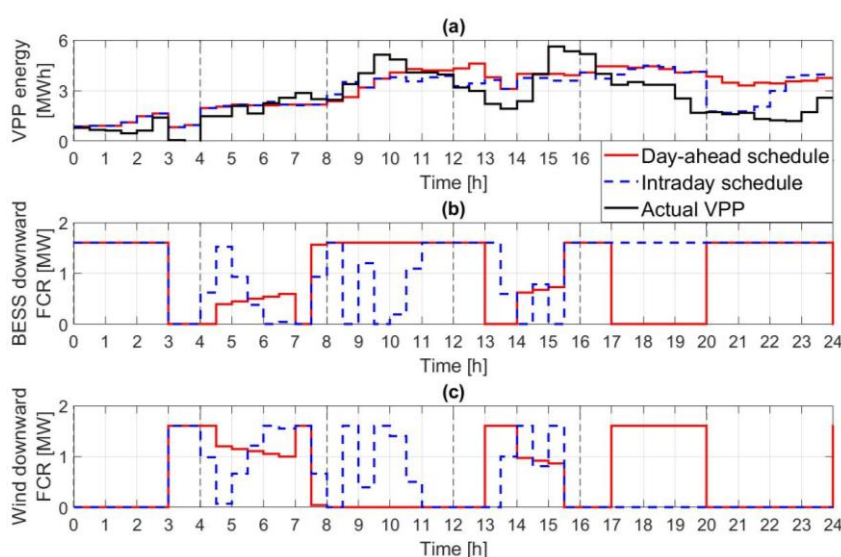


FIGURE 29. (A) SCHEDULED AND ACTUAL VPP ENERGY, (B) DOWNWARD FCR SCHEDULED FOR THE BESS, (C) DOWNWARD FCR SCHEDULED FOR THE WIND FARM

Thus, the simulations show that **the coupling of the wind farm and the BESS enables the BESS to have the flexibility to perform energy arbitrage while providing FCR**. Indeed, the SoC uncertainty due to FCR activation and forecast errors would prevent the BESS from arbitraging energy, whereas the wind farm can take over if it is optimal or if the predicted wind is sufficient.

As the platform runs 1-second simulations, it is also possible to observe various dynamic phenomena, such as differences in the power and SoC of the BESS between the intraday schedule and the actual value, as shown in Figure 30. For instance, from 6am to 7am, the actual SoC deviates downward from the intraday updated schedule (Figure 30(b)). This is the result of the FCR activation following grid frequencies remaining below 50 Hz during a significant period while the BESS is providing 1.6 MW of upward reserve.

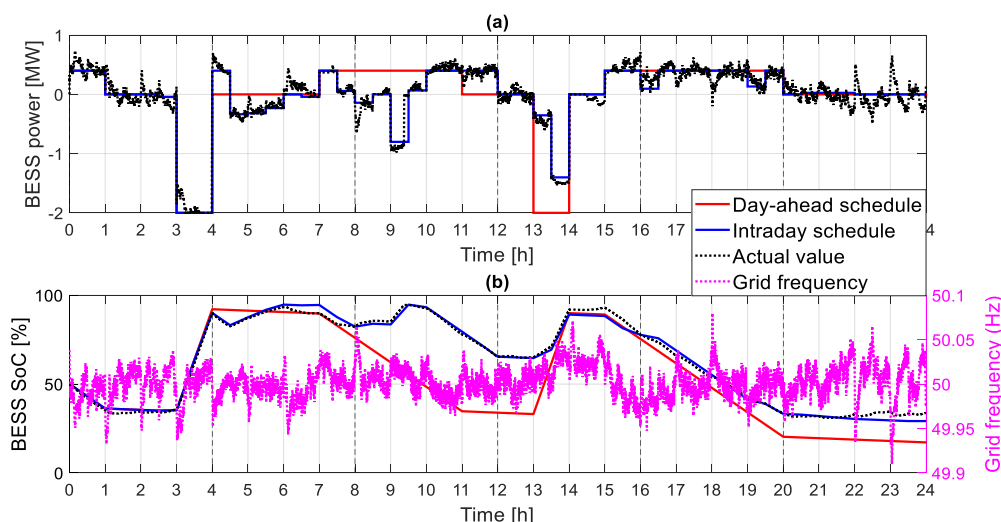


FIGURE 30. (A) SCHEDULED AND ACTUAL BESS POWER, (B) SCHEDULED AND ACTUAL BESS SOC, AND GRID FREQUENCY

Economic results can also be computed day by day, for a whole year for example, which is useful to jointly tune the different control layers of the VPP. In general, the reality differs from the forecasts of wind and PV generation. In this example, over the whole day, there were 148 MWh of energy available according to the day-ahead forecast, 137 MWh according to the intraday forecast and 121 MWh in reality. As shown in Table 5, the loss in revenue can therefore be significant when imbalance costs are accounted for.

Obtained by	Positive imbalance revenues (€)	Negative imbalance costs (€)	Final revenues (€)
The OPS	109.52	-1252.28	9041.50 ⁸
The platform	423.42	-3314.93	7292.74

TABLE 5. DAILY REVENUES EXPECTED BY THE INTRADAY SCHEDULE FROM THE OPS AND SIMULATED BY THE PLATFORM

⁸ The day-ahead energy and FCR revenues amount respectively to 9053 € and 1131 €. While considering the additional revenue from positive imbalances (+109.5 €) and the penalties due to negative imbalances (-1252 €), the final day-ahead predicted revenues turn out to be 9041.5 €.

Lastly, the performance of the ancillary services provided by the VPP can be assessed using the 1-second simulation results. For instance, it is possible to verify a posteriori that there was enough wind power to provide the total downward FCR allocated in case of a frequency deviation of +200 mHz. During this day, the volume of downward FCR allocated on the wind farm was guaranteed during 99.96% of the time, thanks to the relatively high wind availability during the period of FCR provision. The ability to deliver FCR can also be checked for the BESS. At any moment of the day, since symmetric reserve is allocated on the battery, its SoC level must allow a charge or discharge with an energy needed to face respectively a frequency of 50.2 Hz or 49.8 Hz for 15 minutes. This criterion was met 98.93% of time during the day.

3.4 ASSESSMENT OF ECONOMIC KPIS BASED ON OFFLINE SIMULATIONS

Several KPIs were proposed at the beginning of the project and have been adapted to the work progress, to evaluate the success of the French demonstration in reaching its targets [16]. These KPIs can be grouped in three main categories:

- Economic impacts of the demonstration,
- Compliance to System Operators (SO)' technical needs in terms of flexibility services provision,
- Reliability of the solutions implemented.

Economic KPIs measuring the global performance of the VPP in terms of revenues should be assessed over a sufficiently long operating period in order to be representative and conclusive. As previously mentioned, for the sake of cost and time savings, these KPIs were evaluated through offline simulations of the full VPP operation over 5 continuous weeks. The assessment results are presented and discussed in the following paragraphs, while technical KPIs of 2 other categories were analyzed by post-processing experimental data, of which the results will be showcased in the next chapter.

3.4.1 VALUE OF MULTI-SERVICES PROVISION

The first economic KPI as defined in Table 6 aims to assess whether the participation of the VPP in FCR could bring an additional gain, compared with the traditional management strategy of performing energy arbitrage only in the Spot market⁹.

KPI n°1			
KPI name	Increase in revenue of the VPP by providing multi-services	KPI ID	IR1
Main objective	Assess the increase in revenue by providing frequency regulation services such as FCR in addition to the only energy purchase/sale (i.e. energy arbitrage).		
KPI Description	A VPP composed of renewables and storage could contribute to providing ancillary services such as frequency containment reserve, in addition to the		

⁹ To know more details about the basics of the French wholesale electricity market, one can refer to the website of CRE (Commission de Régulation de l'Énergie): <https://www.cre.fr/en/Electricity/Wholesale-electricity-market/wholesale-electricity-market> and the website of EPEX SPOT: <https://www.epexspot.com/en/basicpowermarket>.

	traditional energy arbitrage in the Spot market. Within the VPP, the use of the operational planning scheduler will help make optimal decisions when providing multiple services to maximize the global revenue of the VPP. This will encourage new players to participate in ancillary service markets.
Unit	%
Formula	$IR1[\%] = \frac{G_{EUSysFlex} - G_{BaU}}{G_{BaU}} \times 100\%$ <p>Where:</p> <p>$G_{EUSysFlex}$ [€] is the VPP revenue when ancillary services are provided.</p> <p>G_{BaU} [€] is the VPP revenue in the BaU (Business as Usual) scenario (the only activated service is the energy arbitrage).</p>
Target value	> 0
Baseline scenario	Without EU-SysFlex innovation: assets aggregated for electricity energy purchase/sale; no frequency service is provided.

TABLE 6. KPI N°1: INCREASE IN REVENUE OF THE VPP BY PROVIDING MULTI-SERVICES

After computing the global revenue of the VPP running over weeks, it has been calculated that $IR1 = 7.23\%$ according to the formula in Table 6, meaning that **the provision of FCR in addition to energy arbitrage makes the VPP revenue increase by 7% on average, while helping meet the needs of flexibility and ancillary services of the power system.**

Indeed, while performing energy arbitrage, the BESS is used mainly when prices are at the lowest (for charging from renewable energies) or the highest (for discharging). For the remaining period, the battery is only a bit charged to counter the effect of loss of energy for FCR provision or discharged to reduce the impact of forecast errors and imbalance penalties. Therefore, it is economically interesting for the VPP to provide the FCR service when energy prices are not extreme, as the BESS is largely available during this period of time. Although its charging and discharging capacities cannot be fully mobilized while participating in FCR¹⁰, it still turns out to be a good compromise.

When the FCR price is high, it could be sometimes decided by the OPS to provide the maximum level of FCR, i.e. 1.6 MW, while storing energy only with the remaining capacity, i.e. 400 kW, as illustrated in Figure 31 and Figure 32 between Hour 96 and 101.

However, on the same graphs between Hour 112 and 116, one can see that when the Spot price is high and the FCR price is quite low, the OPS decides to reduce the VPP contribution in FCR so as to sell more energy at a good price. Indeed, in these hours the SPOT price can reach up to 61 €/MWh and has a difference of about 30 €/MWh on average comparing with that of off-peak hours, whereas the FCR price falls to 2 €/MW/h. Knowing that a

¹⁰ As explained in Footnote 7 (Section 3.3.1), 25% of the power capacity should be reserved for the energy reservoir management when providing the FCR service.

reduction of 0.6 MW of FCR provision (Figure 31(b)) allows to discharge 0.6 MWh of more energy at the 113th hour (Figure 32(b)), a simplified and approximative calculation could show that this decision only causes a loss of 4.8 € ($2 \times 4 \times 0.6$) but results in a gain of 18 € (30×0.6). If the FCR price had been higher (e.g. 8 €/MW), the revenue for providing 0.6 MW of FCR during 4 hours would have amounted to 19.2 € ($8 \times 4 \times 0.6$), and the OPS might not have chosen to reduce the FCR volume.

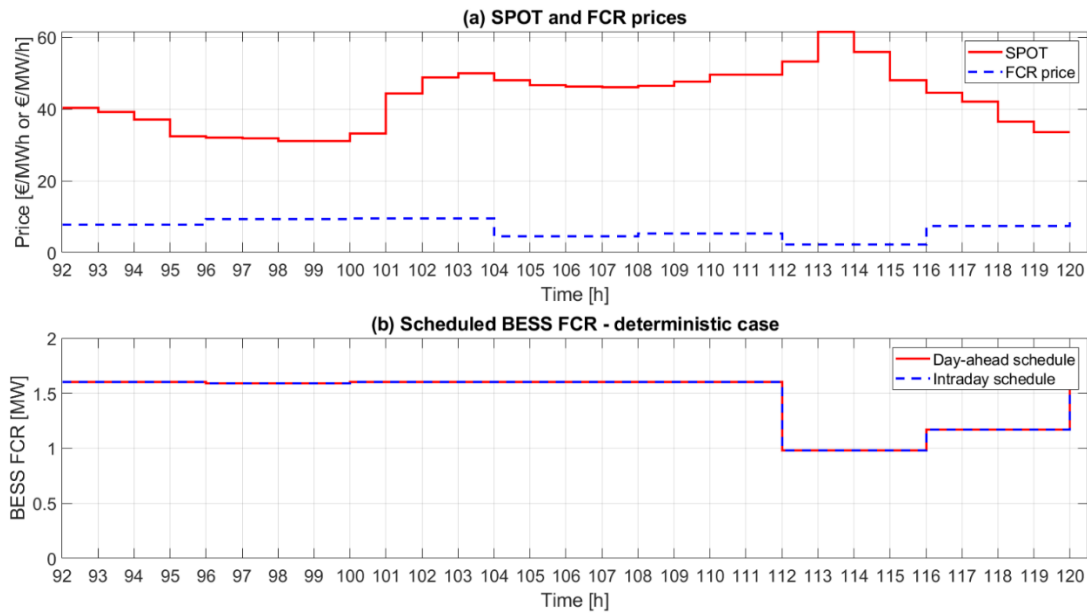


FIGURE 31. EXTRACT OF THE 5-WEEK SCHEDULES: (A) SPOT AND FCR PRICES, (B) SCHEDULED BESS FCR

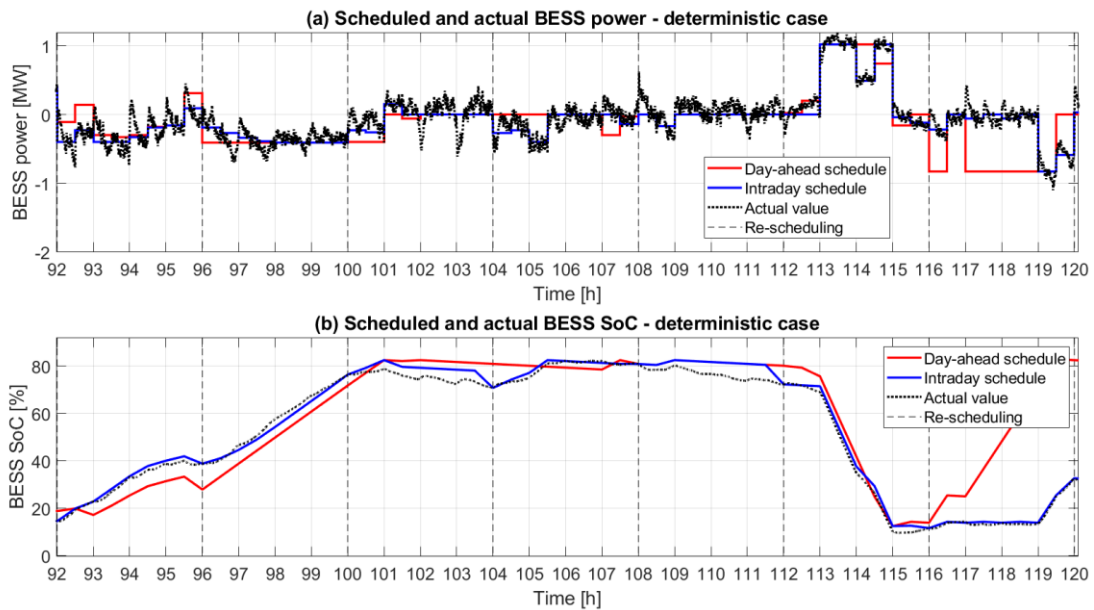


FIGURE 32. EXTRACT OF THE 5-WEEK SIMULATIONS: (A) SCHEDULED AND ACTUAL BESS POWER, (B) SCHEDULED AND ACTUAL BESS POWER SOC

One arguable issue is that the participation in FCR leads to an additional uncertainty on the SoC level (Figure 32(b)), which could sometimes prevent the VPP from respecting its commitment in the Spot market. Apparently, the simulation results tend to show that the gain from the FCR provision is higher than the penalties generated by this uncertainty. Note that in any case, larger uncertainties related to forecast errors are always present in the VPP management.

3.4.2 INTEREST OF THE FCR PROVISION BY MULTI-RESOURCES

The second KPI as defined in Table 7 aims at assessing whether the participation of both the wind farm and the storage in FCR would help increase the global revenue of the VPP, compared to the case where only a single unit is used to provide this service.

KPI n°2			
KPI name	Increase in revenue of the VPP by allocating reserve on multi-resources	KPI ID	IR2
Main objective	Assess the increase in revenue by allocating the committed services on multiple resources within the VPP.		
KPI Description	In a context of aggregation of various assets, the services committed at the VPP level could be procured from different resources when they are available. For example, both wind generators and battery storage have the technical capability of providing symmetrical frequency reserves. The optimal way of reserve allocation inside a VPP depends on the availability and the operating point of each asset controlled, as well as on its use in the next scheduling time period. The use of an optimizer will help make optimal decisions when managing multi-resources for FCR provision, in order to maximize the global revenue of the VPP.		
Unit	%		
Formula	$IR2[\%] = \frac{R_{EUSysFlex} - R_{BaU}}{R_{BaU}} \times 100\%$ <p>Where:</p> <p>$R_{EUSysFlex}$ [€] is the VPP revenue when frequency containment reserve is procured from various assets, within their allowed technical limits.</p> <p>R_{BaU} [€] is the VPP revenue in the BaU (Business as Usual) scenario, where FCR is only provided either by the battery storage or by the wind farm.</p>		
Target value	≥ 0		
Baseline scenario	Without EU-SysFlex innovation: no coordinated reserve procurement is achieved within the VPP.		

TABLE 7. KPI N°2: INCREASE IN REVENUE BY ALLOCATING FCR SERVICE ON MULTI-RESOURCES

This KPI has been analysed in 2 cases. In the first case, the VPP revenues have been compared, when the frequency containment reserve is allocated on both resources and when the wind farm is the only participating unit (the storage is just used for energy arbitrage).

In this case, $IR2 = 7.23\%$, i.e. the same increase in revenue as that for KPI°1 has been found. Indeed, when a symmetric reserve should be procured totally from the wind farm, the OPS chooses to almost never position the VPP in the FCR market, as if the only service activated were the energy arbitrage. This is because the provision of upward reserve by the wind farm implies significant curtailment of its generation, leading to important shortfalls for energy sales in the Spot market, which can almost never be compensated by the FCR participation (with respect to the FCR and Spot prices applied in the case study coming from recent market data). Generally, to find an economic interest for the VPP to provide the FCR in this case, the price of the service should be at least at the same level as the daily peak-to-valley height of the Spot price.

The obtained result can also be interpreted from another angle: **the economic opportunities of wind generation for the participation in FCR are highly increased, if coupled with storage systems and managed in a coordinated way, as useless renewable generation curtailment and financial shortfalls can be avoided.**

The second studied case consists in comparing the VPP revenues when both the wind farm and the storage provide FCR and when all the reserve is allocated on the storage only. It has been found that $IR2 = -0.35\%$ in this case. This result as a negative value does not seem intuitively understandable – one of the possible explanations could be the inaccuracy of the BESS model considered by the VPP scheduling. Indeed, this simplified model was initially built based on the assumption that the FCR response is always symmetrical and could not precisely describe the evolution of the SoC while the BESS is providing asymmetric reserves. However, when both assets are available for FCR provision, the OPS tends to allocate upward reserve on the storage and downward reserve on the wind farm, in order to maximize the revenue. Since the storage responds only to underfrequency events in this case, there are larger actual SoC deviations than modelled and expected by the scheduler, and thus, leading to higher negative imbalances at the VPP level.

For example, the figures below show an extract of power imbalances of the VPP during the first tens of hours of the simulation, in the respective scenarios where the FCR is provided by both assets (Figure 33) and by storage alone (Figure 34). As can be seen from Hour 21 to 24, more negative power imbalances of 2 MWh (at a cost of about 53 €/MWh) can be observed in the first scenario, which costs about 110 €, whereas the total difference of imbalance costs in the first week is only 160 €. For the whole week, 4% more negative imbalances have been observed, which are greatly penalized, when both the wind farm and the storage contribute to FCR provision.

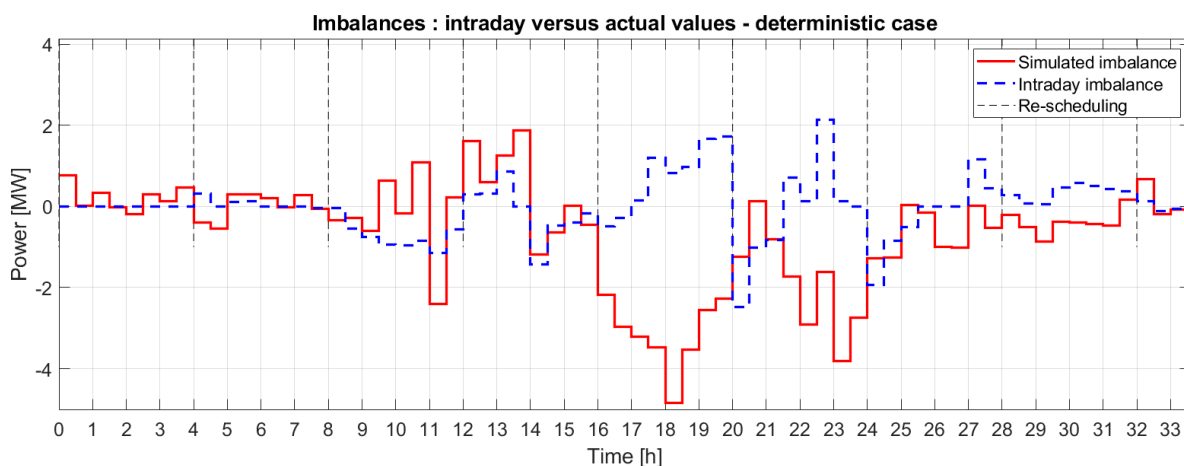


FIGURE 33. EXTRACT OF THE 5-WEEK SIMULATIONS: IMBALANCES WHEN FCR IS PROVIDED BY BOTH RESOURCES

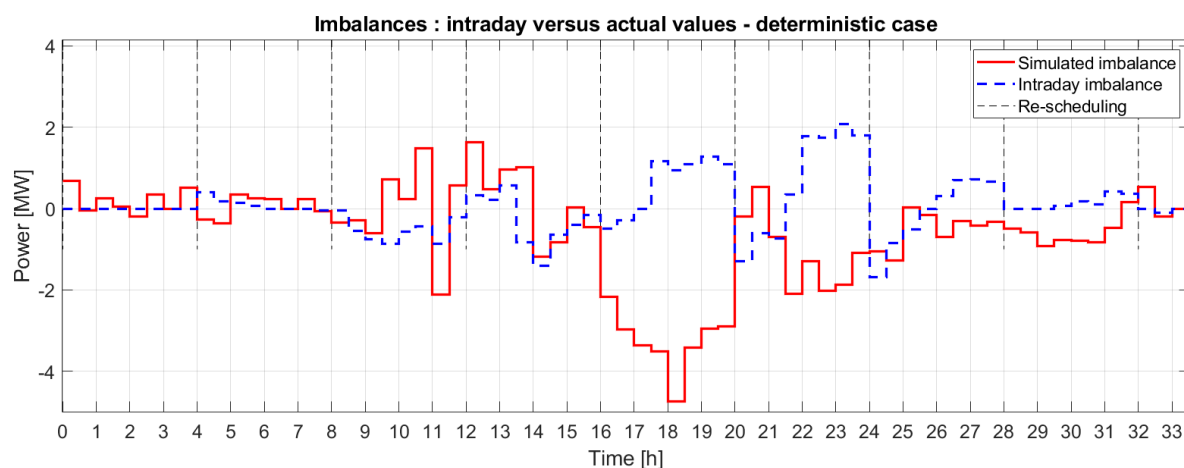


FIGURE 34. EXTRACT OF THE 5-WEEK SIMULATIONS: IMBALANCES WHEN FCR IS PROVIDED BY STORAGE ALONE

Note however that these additional imbalance settlement costs should have disappeared if the SoC deviations in case of asymmetric FCR provision had been more accurately modelled, and $IR2$ in this case would have been equal to or larger than zero as expected.

In conclusion, the assessment of the second KPI reveals that **it is beneficial to have a joint participation of the wind farm and the storage in FCR provision** when they are available. Along with the result of the first KPI, **the economic interests of the French demonstration, based on the approach of "multi-services provision by multi-resources", have been proven.**

3.4.3 INTEREST OF STOCHASTIC PROGRAMMING APPROACHES

The definition of the third economic KPI is described in Table 8. This KPI aims to analyse the interest of the program scheduling based on stochastic optimization for the VPP management, with a focus on the mitigation of power imbalances.

KPI n°3			
KPI name	Reduction in power imbalances by application of stochastic optimization	KPI ID	IMB
Main objective	Assess the reduction in power imbalances of the VPP while performing stochastic programming.		
KPI Description	Given that no guaranteed feed-in-tariffs for the PV and wind generation are considered in the demonstration, the net energy provided/consumed by the VPP has to be sold/purchased on the electricity market. Deviations from day-ahead and intraday schedules are valued at the positive/negative imbalance settlement prices, which are "penalizing" compared to the Spot prices. Therefore, it seems economically interesting to reduce power deviations from the committed schedules at the VPP level, which may be achieved by applying a scenario-based stochastic optimisation.		
Unit	%		
Formula	$IMB[\%] = \frac{IMB_{stochastic} - IMB_{deterministic}}{IMB_{deterministic}} \times 100\%$ <p>Where:</p> <p>$IMB_{stochastic}$ [MWh] is the negative power imbalances when the VPP schedules are generated by applying stochastic programming.</p> <p>$IMB_{deterministic}$ [MWh] is the negative power imbalances when the VPP schedules are generated by applying deterministic programming.</p>		
Target value	< 0		

TABLE 8. KPI N°3: REDUCTION IN POWER IMBALANCES BY APPLICATION OF STOCHASTIC SCHEDULING

This KPI has been assessed by simulating energy arbitrage of the VPP over 5 weeks with different scheduling approaches. It has been revealed that more than 4% of negative power imbalances can be mitigated when the stochastic optimization is applied ($IMB = -4.5\%$). As a consequence, it also helps increase slightly the VPP actual revenue of 0.25% in the end.

Indeed, the stochastic optimization has a vision of different possible generation "paths" of renewable energy (based on the knowledge of probabilistic scenarios). By nature, it tends to reduce the variance of economic results with respect to uncertainties. Since negative imbalance settlement is highly penalized in the simulation assumptions considered (its costs amount to 1.5 times the SPOT price), when this approach is applied, the OPS decides generally to take safer positions in the Spot market while limiting the risk of having a large amount of negative imbalances. Although these conservative decisions result in 1% less day-ahead revenues, the final actual revenues at the end of the day turn out to be more profitable.

As an example, an extract of about 30 hours of the VPP schedules, calculated by applying different optimization approaches, is illustrated in Figure 35. It can be seen that, for the same day and the same forecasts, the schedules

committed by a deterministic programming are almost always higher than that committed by a stochastic programming¹¹ (Figure 35(a)). These bolder decisions finally induce more negative imbalances and associated handling costs (Figure 35(b)).

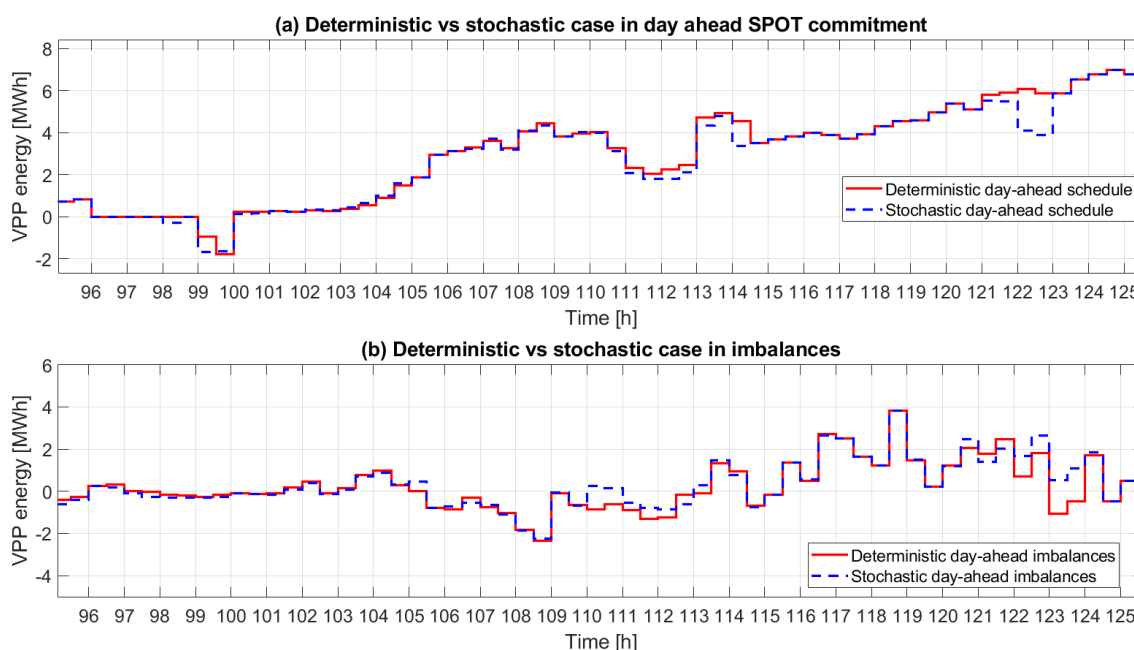


FIGURE 35. COMPARISON BETWEEN DETERMINISTIC AND STOCHASTIC PROGRAMMING: (A) DAY-AHEAD SCHEDULES, (B) IMBALANCES

From the VPP operation point of view, **a VPP operating program scheduling based on stochastic optimization has been proven effective to reduce costly power imbalances with respect to the commitments and entails higher overall revenues.** Indeed, as presented hereinbefore, the stochastic scheduling helps slightly increasing the VPP revenue even under unfavourable conditions (forecast errors are highly penalized, whereas the generation of probabilistic scenarios voluntarily introduces further variations). The increase in revenue thanks to the application of stochastic programming is therefore expected to be higher under less penalizing assumptions, which are closer to that observed in the very recent electricity market.

Seen from the perspective of the overall power system, the mitigation of the power and energy imbalances due to the variability of RES, by means of portfolio management of distributed resources through advanced scheduling approaches, could foster a smoother and easier integration of renewable generation, and thus, lead to a more stable power system operation.

¹¹ The 40%, 50% and 60% quantiles of the wind and PV forecasts were used to create probabilistic generation scenarios for stochastic scheduling.

4. EXPERIMENTAL DEMONSTRATION OF THE MULTI-SERVICE VPP AND ASSESSMENT OF TECHNICAL KEY PERFORMANCE INDICATORS

Local tests were first performed in 2020, at Concept Grid and at *Anglure* wind farm, to demonstrate the flexibility services provision by each controllable resource within the VPP. Main results and findings of these tests will be summarized in the first section of the present chapter. More details can be found in the previous WP8 report [4].

In early 2021, the communication platform was fully implemented and commissioned, which allowed the remote control of all the local assets via the centralised EMS. Many hours of experiments were then successfully carried out to demonstrate the complete and autonomous operation of the VPP. Analysis of the experimental results as well as the assessment of some technical KPIs related to the behaviour of the VPP during the full-chain experiments will be given in the second section.

4.1 DEMONSTRATION OF FLEXIBILITY SERVICES PROVISION

The objectives of the first tests are to validate the performance of the control algorithms implemented in the local real-time controllers of the wind farm and the BESS, and to perform algorithms debugging and controllers tuning if necessary. Different flexibility services were activated manually using fake signals or real measurements, one after another, on the storage controller E-SCU and on the wind controller FCU, to verify the dynamic behavior of each resource. The centralized management of the VPP including forecasting and optimization as well as the communication systems are not involved in this phase of the demonstration.

4.1.1 FREQUENCY CONTAINMENT RESERVE

FCR delivery consists in modulating the active power around a baseline power (P_0), with an additional power proportional to the frequency deviations from its reference value as shown in *Eq. 1*.

$$P_{ref}(t) = P_0(t) + k * (f_{ref} - f(t)) \quad \text{EQ. 1}$$

With:

- k : FCR gain (in MW/Hz),
- f_{ref} : reference frequency (50 Hz in Europe),
- P_{ref} : actual active power reference.

The technical capability of a battery storage to contribute to the FCR service has been largely proven and the participation of BESS in the FCR market has been industrialized in global projects. However, to our knowledge, the FCR provision by wind generation has not been fully investigated in the literature and still needs to be demonstrated in real grid conditions.

4.1.1.1 RESERVE CONSTITUTION

Unlike conventional power plants or storage having nearly fixed baseline power for each dispatching period¹², the reserve constitution on wind generators is more complex. Indeed, when no reserve is allocated, they are operated to maximize the output, resulting, at a given instant, in a $P_0(t)$ equal to their maximum available active power level, known as wind 'AAP (available active power)' or P_{AAP} .

P_{AAP} level corresponds in theory to the maximum power that would have been produced by a wind farm without any generation curtailment and is continuously changing due to its wind dependency. When a wind farm provides power reserve, its P_{AAP} level can only be assessed through a specifically designed estimation approach but cannot be directly measured on site. This could therefore lead to an estimation error, i.e. a difference between the estimated AAP (P_{AAP_est}) and the actual AAP (P_{AAP}). Once the available power of a wind farm is assessed, to allow upward reserve, the wind farm must be operated below this estimated "maximum" generation P_{AAP_est} , leading to the baseline operating point $P_0(t)$ as calculated in Eq. 2.

$$P_0(t) = P_{AAP_est}(t) - P_{res_up_max}$$

EQ. 2

With:

P_{AAP_est} : estimated wind available active power,

$P_{res_up_max}$: maximum allocated upward reserve.

The constitution of positive and/or symmetrical reserve will result in a consistent energy loss as represented with the dotted area in Figure 36 (a). Without voluntarily curtailing the wind generation output, only downward reserve (i.e. asymmetrical reserve) can be provided as shown in Figure 36 (b). In this case, P_{res_max} can be set to zero, and P_0 turns out to be equal to the estimated $P_{AAP}(t)$.

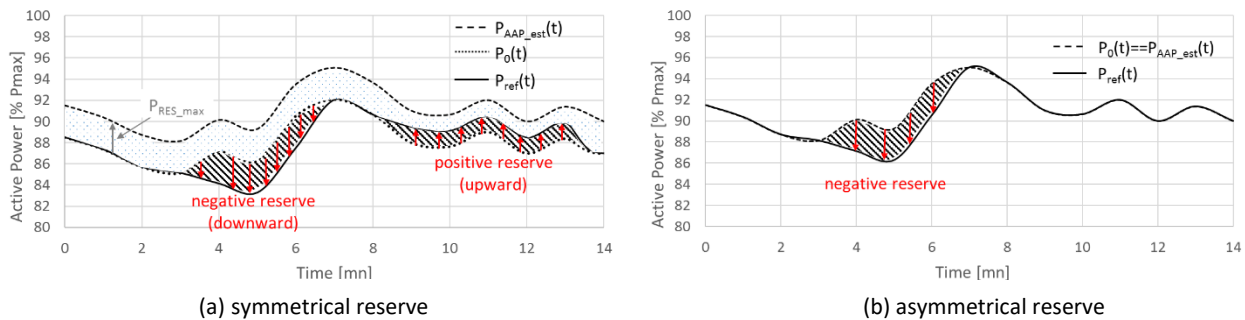


FIGURE 36. ILLUSTRATION OF WIND RESERVE CONSTITUTION AND DELIVERY

The capability of estimating every second its maximum available active power is therefore key to allow the provision of frequency services for a wind farm. In the EU-SysFlex demonstration, the applied estimation method was based on an ENERCON patented solution, which is described in detail in [14] and [17].

¹² For a conventional power plant such as a coal-fired thermal plant or a nuclear power plant, the baseline power corresponds to its dispatched power reference for each time step.

4.1.1.2 DYNAMIC BEHAVIOUR

The storage FCR response was first assessed by activating this service with different parameter settings through the RT simulator of Concept Grid, which enables Modbus communication with E-SCU. One illustrative example is shown hereinafter: 1600 kW of symmetrical FCR reserve was allocated on the storage and was set to be fully delivered to the grid for ± 30 mHz of frequency deviation with a time response (at 99%) of 30 seconds. In the current French power system, the full FCR should be provided at ± 200 mHz as required by the grid code. However, since such important frequency deviations are rarely observed in practice, a narrower frequency regulation band was applied during the local tests to evaluate the FCR performance in the full regulation area.

A 100-minute extract of the BESS dynamic behaviour while providing FCR is shown in Figure 37. The power measured at the PoC (blue curve in Figure 37(b)) corresponds to the sum of the power allocated for FCR (yellow curve) and the power dedicated to SoC control¹³ (red curve). It can be observed that the FCR response was correctly delivered to the power system in opposition to the frequency deviations (Figure 37(a)). 1600 kW of power reserve was effectively injected when frequency dropped below 49.97 Hz and absorbed when frequency goes beyond 50.03 Hz. The time response of the FCR was also coherent with the pre-set control parameter (full activation within 30 seconds).

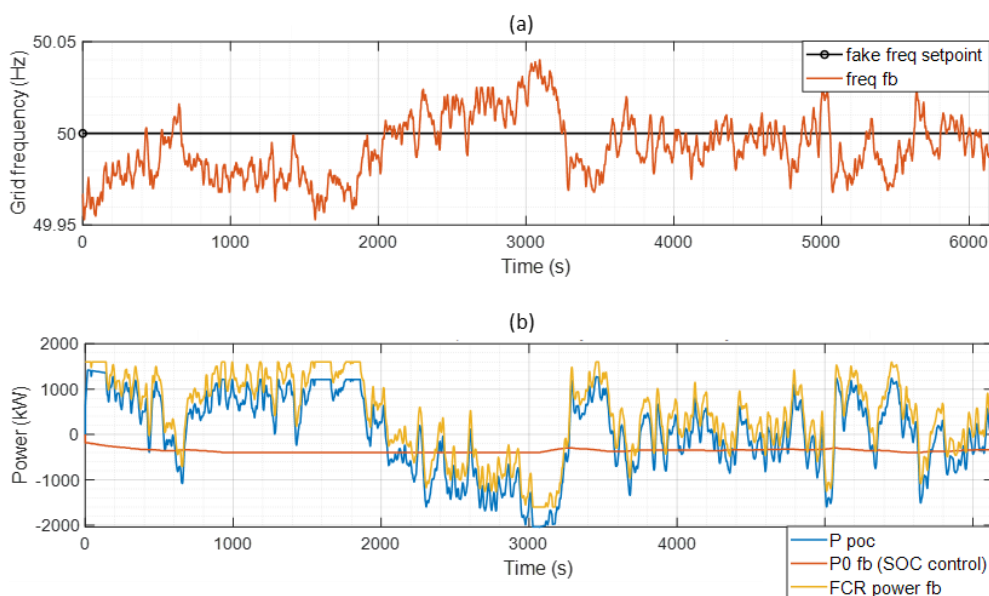


FIGURE 37. PROVISION OF FCR BY STORAGE: (A) GRID FREQUENCY, (B) POWER AT POC, SOC CONTROL POWER AND FCR POWER¹⁴

On the wind farm side, two tests of 4 hours each were performed with the provision of 1 MW symmetrical FCR. In the test n°1, the wind farm was set to deliver the full FCR within a reduced range of frequency deviation of ± 50 mHz, to verify the wind dynamic behaviour and to observe the full reserve release when the frequency thresholds were reached.

¹³ To ensure a continuous FCR provision by storage, the control of its SoC is essential by absorbing power from the grid to compensate energy loss.

¹⁴ During this test, the fake frequency signal was set to zero and real grid frequency was used as input of the FCR controller.

Figure 38 shows a 14-minute extract from the complete test, the actual wind power P_{actual} reached the estimated AAP (P_{AAP_est}) when the frequency dropped to 49.95 Hz (after 01:00), thereby providing 1 MW of full FCR as expected. It was also observed that the wind farm could provide correctly full downward FCR, when the frequency was around 50.05 Hz at 00:58, by decreasing its power to the expected level, equal to the estimated AAP minus twice the amount of FCR¹⁵.

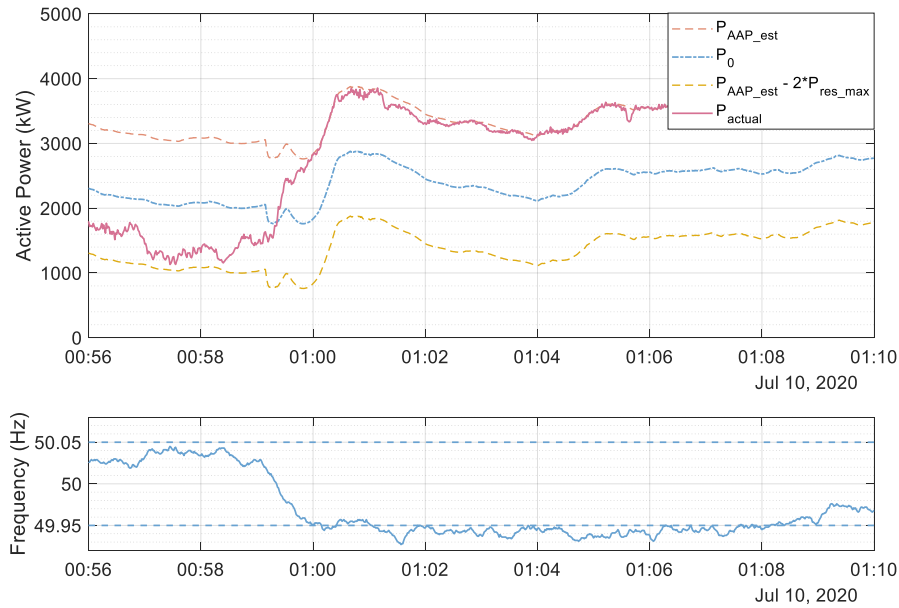


FIGURE 38. WIND FCR DELIVERY OF 1 MW @ 50 MHZ (EXTRACTED DURATION: 14 MINUTES)

The dynamic criterion was also checked through the data analysis of the test n°1 results. It was found that the equivalent constant time of the FCR regulation from the wind farm is around 1 second. Given this dynamics, the wind farm satisfies easily the full activation delay criterion for the FCR qualification.

4.1.1.3 GAIN ASSESSMENT

Besides the FCR response time, another important performance criterion focuses on the FCR gain (k in Eq. 1). According to the current rules of the French TSO RTE [18], if one asset provides FCR with an actual gain differing by more than 20% from the contracted value, for more than 10% of the monitored period, the service is then considered as partially unavailable. In other words, to comply with RTE's requirements, the FCR gain assessed must mostly remain between 80% and 120% of the contracted value.

In order to assess the actual FCR gain k , the same method as recommended by RTE [19] was used. This method consists in estimating k and P_0 from Eq. 1 at the same time by applying the least squares method on the measurement data of the actual power at PoC and the grid frequency, acquired with a 10-second periodicity. This method is mathematically possible to be applied to assess the FCR performance for conventional power plants (of which the baseline operating point is almost constant piecewise at each scheduling time step) and for battery

¹⁵ Full downward FCR delivery: $P_{expected}(t) = P_0(t) - P_{res_max} = P_{AAP_est}(t) - 2 * P_{res_max}$.

storage (of which the form of the baseline operating point is well-known, e.g., constant and continuous ramps for SoC control).

However, for wind generation, the baseline power P_0 varies continuously depending on wind conditions, which makes it complicated to dissociate the power variations from the FCR regulation (i.e. frequency variations) and that from wind variability. The highly variable and – in the range of few seconds – unpredictable shape of the estimated AAP makes it mathematically impossible to get precise FCR gain assessment without knowing P_{AAP_est} . For this reason, it is recommended that the estimated AAP should be known by the TSO as an input, while applying the least squares method for the estimation of the actual gain of wind FCR.

The performance on FCR gain is supposed to be high when the reserve is provided by the BESS. To verify this, the actual gain was assessed for the local test described in Figure 37. Two different methods were applied, assuming that the exact value at every moment of the SoC control power P_0 was "known" (method 1) or not (method 2) by the TSO while assessing the FCR performance.

Figure 39 illustrates the comparison between the estimated FCR gain using both methods with the contracted or targeted value (provision of 1600 kW of FCR @ ± 30 mHz, i.e. $k_{target} = 1.6 \text{ MW} / 0.03 \text{ Hz} = 53.3 \text{ MW/Hz}$) for the whole period of the test. The two dotted lines correspond respectively to the minimum (80%) and maximum (120%) authorized thresholds. It was observed that although the assessed FCR gain was a little lower than the target value, which was partially due to the non-optimal SoC control during this test, it remained globally within the allowable range regardless of the method used. As expected, **the experimental results proved a very good dynamic and static performance of the FCR provided by the BESS.**

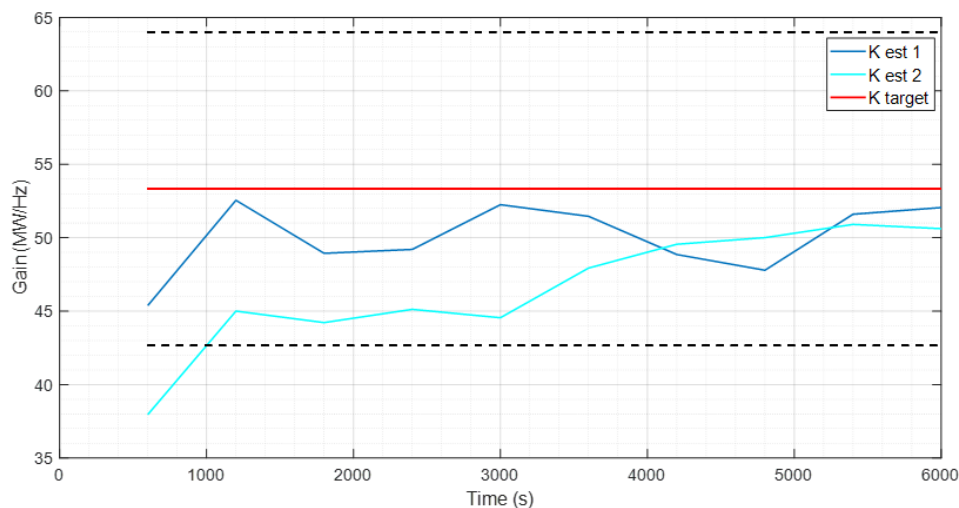


FIGURE 39. PERFORMANCE ASSESSMENT OF FCR GAIN

To evaluate if the FCR provided by wind generation could also satisfy the static criterion on FCR gain, a second test was carried out at *Anglure* wind farm under real-life FCR activation conditions. Figure 40 shows a 30-minute extract from the full 4-hour test. In this testing scenario, the contracted gain $k_{contracted}$ equals 5 MW/Hz, considering 1 MW of wind FCR which should be fully delivered for a frequency deviation of ± 200 mHz.

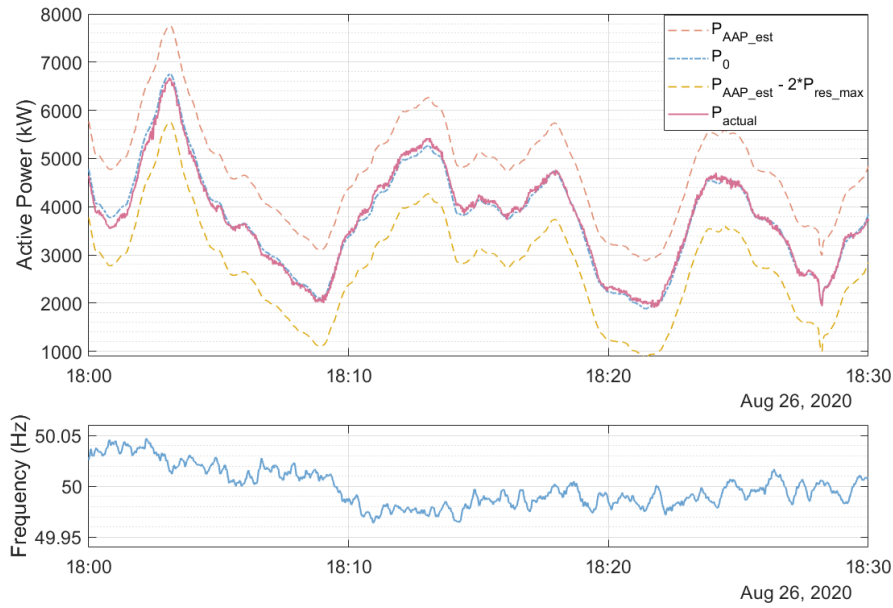


FIGURE 40. WIND FCR DELIVERY OF 1 MW @ 200 MHZ (EXTRACTED DURATION: 30 MINUTES)

To better illustrate the wind FCR regulation error (i.e. difference between the actual gain k and the contracted gain $k_{contracted}$), the expected FCR response $P_{expected}$ was calculated by applying the contracted FCR gain ($k_{contracted}$) to Eq. 3. This $P_{expected}$ value corresponds therefore to the 'ideal' FCR regulation, based on the estimated AAP, for a given frequency variation.

$$P_{expected}(t) = P_{AAP_est}(t) - P_{res_max} + k_{contracted} * (f_{ref} - f(t)) \quad \text{EQ. 3}$$

Figure 41(b) shows the obtained results on FCR actual gain assessment. During this 4-hour test, the estimated FCR gain remained within the allowed range (4 and 6 MW/Hz, i.e. $\pm 20\%$ of the contracted gain of 5 MW/Hz) for 87.5% of the observation time. In the first 10-minute period, the FCR gain appeared to be twice as large as the contracted value of 5 MW/Hz. Figure 41(a) shows that a corresponding FCR regulation error of nearly 1 MW (i.e. difference between the actual power and the expected power) can be found in this period.

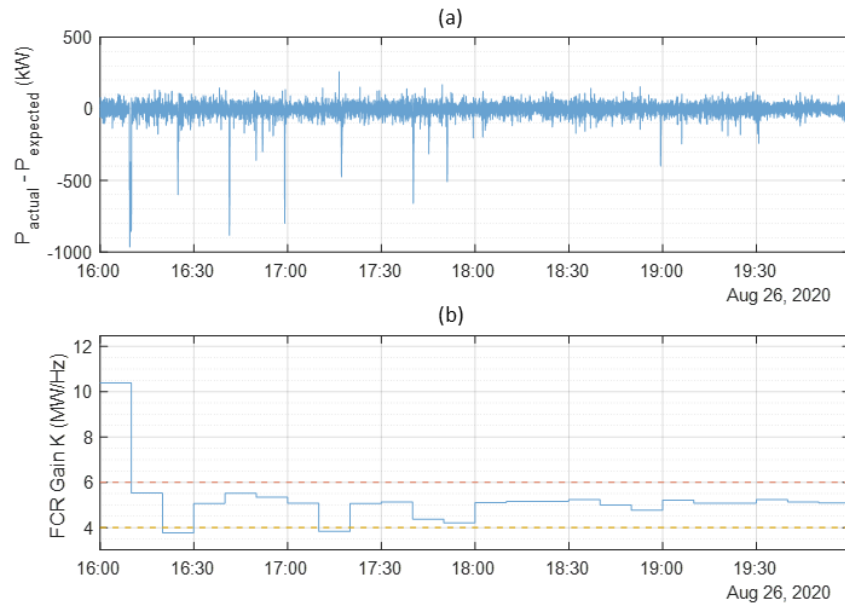


FIGURE 41. WIND FCR GAIN PERFORMANCE ASSESSMENT: (A) DIFFERENCE BETWEEN THE ACTUAL AND THE EXPECTED POWER, (B) ESTIMATED FCR GAIN

Indeed, as illustrated in Figure 42, a zoom on the dynamic behaviour of the wind farm during this period reveals that the wind power generated was much lower than P_0 for about one minute (16:09 – 16:10), whereas the grid frequency was merely above 50 Hz (i.e. little downward reserve should have been activated in this time window). The unusual large power decrease comes from the overestimation of the AAP level, resulting in a misleading FCR gain assessment and consequently in a poor FCR performance. During the EU-SysFlex experimentations, the overestimation of the AAP was mainly observed when wind generation decreased.

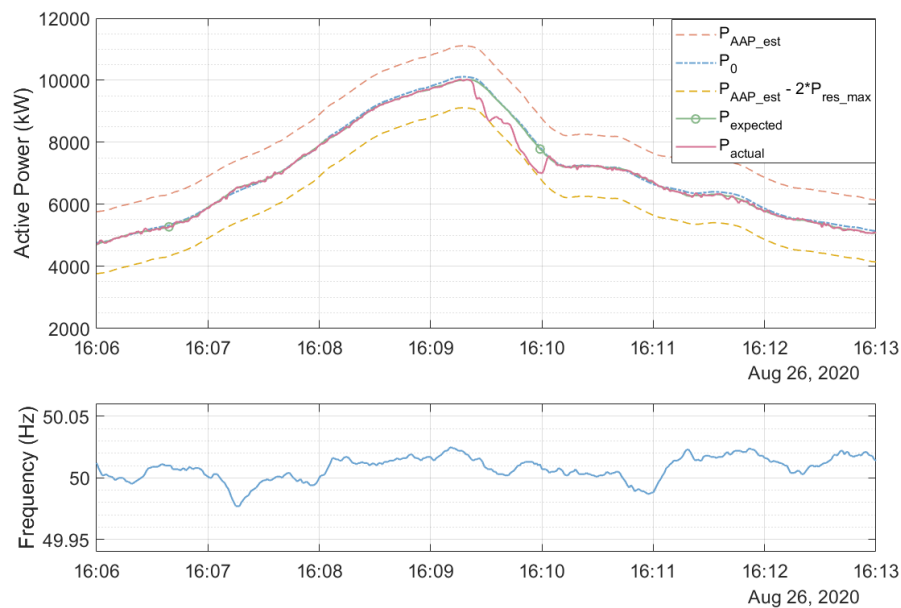


FIGURE 42. AAP ESTIMATION ERROR IMPACTING FCR PROVISION PERFORMANCE

The two other periods when the estimated FCR gain is out of the allowed range (Figure 41) are also linked to the saturation of P_{actual} due to the overestimation of the AAP. In contrast, an underestimation of the AAP leads to an over-curtailment of wind power for reserve constitution, i.e. an additional wind energy loss, but a priori, would not affect the gain assessment.

The experimental results show that **although wind generation is of variable nature, it is technically capable of providing effective FCR service. The real-time estimation of the wind AAP is essential to allow FCR provision and the quality of this estimation highly impacts the performance of the FCR service procured from wind generation.** According to the analysis of the measurements from the local tests, the actual wind FCR performance seems globally compliant with the current TSO's requirements in terms of dynamics and gain, although over-estimation of wind AAP could lead to occasional under-performance.

As previously mentioned, the FCR provision has been integrated in the EMS management of the VPP (see Section 2.2.2.1). This service was therefore further assessed when it was jointly provided by both the wind farm and the BESS during the full-chain VPP experiments. The assessment results will be presented later in this chapter.

4.1.2 OTHER FLEXIBILITY SERVICES

Besides the FCR, other flexibility services that were supposed to be demonstrated in the French VPP have not been integrated in the centralized control and management for different reasons:

- Regarding the FFR, this service generally needs to be delivered to the power system within not more than 1-2 seconds. Therefore, its required reaction time is faster than the computing cycle time of the EMS (over 2-3 seconds¹⁶) and it can only be activated at the level of each resource according to local measures.
- Regarding the FRR, this service can be modeled in the OPS without any major difficulties. However, the EU-SysFlex French demonstration was not initially sized to provide continuously the FRR service. Indeed, in the current power system, the full delivery of the aFRR could be maintained during several hours by the TSO for system needs. Therefore, a huge amount of energy capacity of the storage should be available, or otherwise wind generation would be materially curtailed, to successfully provide symmetric FRR.
- Regarding the ramp rate control, this service is not compatible with any other active power services. Indeed, due to the relatively small size of the battery (2MW / 3MWh), compared to that of the renewable generation fleet (18 MW of nominal power), when the RRC is activated, the full capacity of the storage is generally mobilized to counter fluctuations of the renewables and other services can hardly be procured from the VPP. Therefore, it does not seem necessary to optimize the provision of this service through the EMS.

¹⁶ Including data reading and writing, data processing, calculation of schedules, data transmission, etc.

In consequence, the technical feasibility of the above-mentioned services was demonstrated, and their performance was evaluated only through the experiments carried out at a local level.

4.1.2.1 FAST FREQUENCY RESERVE

The FFR service is supposed to help the electrical system compensate abrupt and rapid frequency changes due to the increasing penetration of renewables [20]. This service is activated automatically based on the measurement of the grid frequency and generally acts before the FCR response. The control algorithm of FFR implemented in E-SCU and FCU is quite similar to that of FCR with a major difference in terms of response time.

As depicted in Figure 43, the FFR power-frequency chart can be parameterized in the same way as that of FCR and the power setpoints during over-frequency and under-frequency events can therefore be derived.

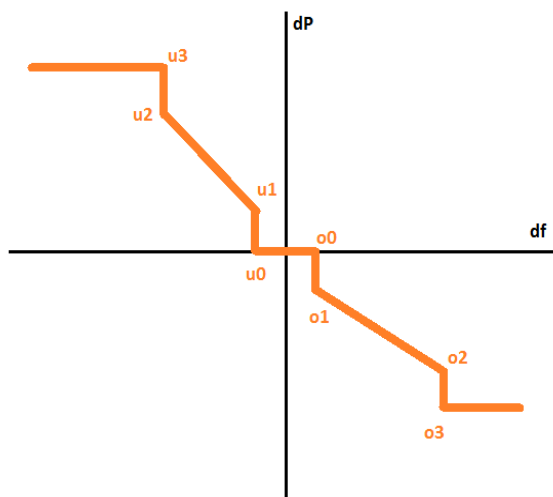


FIGURE 43. FAST FREQUENCY RESERVE PARAMETER CHART

To verify the FFR response of the BESS, its full rated power was used as fast reserve and set to be entirely activated at ± 30 mHz of frequency deviation with a time response (at 99%) of 1s. A dead-band of 10 mHz around 50 Hz was defined during the test to avoid overusing the BESS during "normal" grid disturbances. Note also that while the FFR is provided, the activation of SoC control is not necessary, as this service only reacts to severe grid events and is not supposed to last long in practice, i.e. has little impact on the storage SoC.

Figure 44 shows respectively the measured fast frequency response as well as the grid frequency. It can be observed that the behaviour of the BESS was coherent with the controller parameter settings and the FFR service was triggered only when frequency deviations exceeded the dead-band of ± 10 mHz as expected.

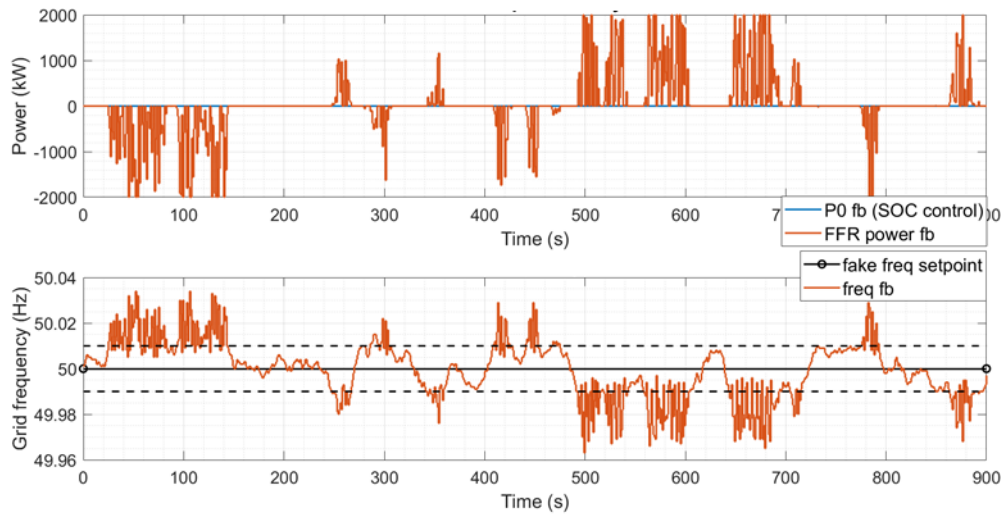


FIGURE 44. FAST FREQUENCY RESPONSE OF THE STORAGE

On the wind side, the dynamics of the FCU controller has been assessed during the local FCR tests and the measured response time was only 1 second (see Section 4.1.1.2), meaning that the wind farm can also technically meet the dynamic criterion of the FFR. Thus, the wind FFR tests have not been performed to avoid repeating the similar tests as achieved for FCR assessment.

Note that the demonstration of the wind inertial emulation (very fast wind power injection by extracting inertial energy stored in the rotating masses and without preset power reserve nor generation curtailment) as depicted in [21] and [22] is out of scope of the present work.

4.1.2.2 FREQUENCY RESTORATION RESERVE

The aFRR service is activated automatically based on a signal sent by the TSO and must be fully activated within 5 minutes. In the French power system, this FRR activation signal corresponds to the “*level N*” generated by the TSO RTE and sent to each power plant participating in FRR service [12]. The “*level N*” is per unit and varies from -1 to +1, meaning respectively the full activation of negative and positive FRR.

A historical “*level N*” profile, which lasted 3 hours as illustrated in Figure 45(b) was used to evaluate the aFRR provided by the BESS. 1 MW of the storage capacity was reserved as FRR and a total power of 250 kW was dedicated to controlling the SoC. It can be observed in the same figure that the aFRR response followed correctly the requested reserve provision as derived from the “*level N*” value at a given time (Figure 45(a)), and the SoC was well maintained (Figure 45(c)) by absorbing power from the grid.

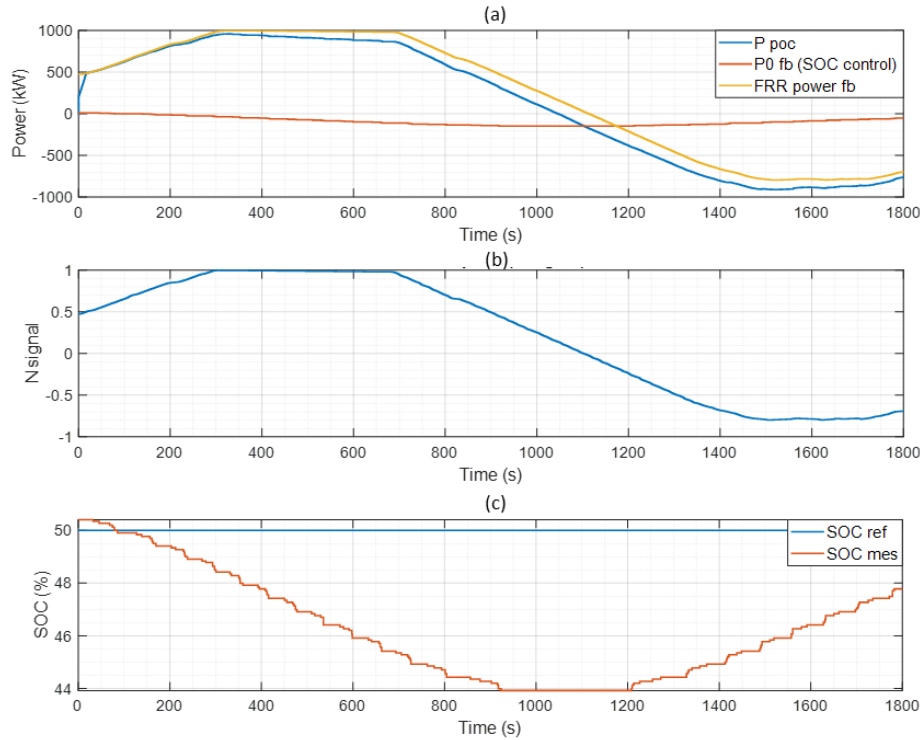


FIGURE 45. AUTOMATIC RESTORATION RESERVE PROVIDED BY THE STORAGE: (A) POWER AT POC, SOC CONTROL POWER AND FRR RESPONSE, (B) FRR SETPOINT (LEVEL N), (C) STATE OF CHARGE

A test of 5 hours using a different historical "level N" profile, as depicted in Figure 46, was carried out at *Anglure* site to assess the FRR response of the wind farm. During the first two hours, only a downward reserve of 1000 kW was allocated on wind generators, whereas a symmetric reserve of 1000 kW was distributed during the remaining 3 hours (Figure 46(b)).

The setpoint plotted in Figure 46(c) corresponds to the per unit value of "level N" multiplied by the reserve volume (1000 kW). In general, it can be observed that the extracted wind FRR response¹⁷ followed correctly at all times the received setpoint, around which were wind-dependent fluctuations and systematic AAP estimation errors.

¹⁷ Wind FRR response = $P_{actual} - P_0 = P_{actual} - (P_{AAP_est} - P_{res_up_max})$, where $P_{res_up_max}$ is the positive FRR reserve.

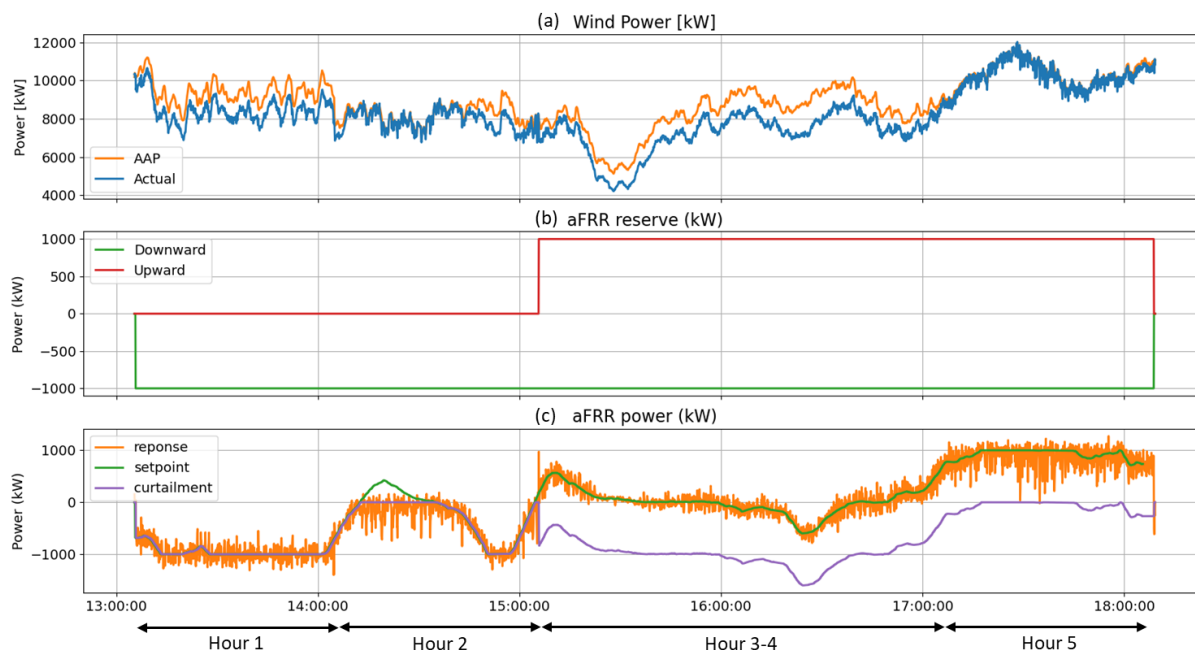


FIGURE 46. AUTOMATIC RESTORATION RESERVE PROVIDED BY THE WIND FARM: (A) ESTIMATED AVAILABLE ACTIVE POWER AND ACTUAL POWER AT POC, (B) FRR RESERVE, (C) FRR SETPOINT AND ACTUAL RESPONSE

More precisely, during the first two hours, wind power was only curtailed when downward FRR should be delivered, i.e. negative “level N ” values were received, and did not respond to any positive setpoints. For example, the wind farm was being operated at its AAP level while the “level N ” was positive between 14:00 and 15:00. Starting from Hour 3, a permanent power curtailment was set at the FRR controller for symmetric reserve constitution. An effective FRR response in both directions was successfully achieved during the 3rd and 4th hours (Figure 46(c)). In the last hour of the test, the wind farm was requested to fully deliver its upward FRR, and therefore, generated a resultant power output at the level of the estimated AAP (Figure 46(a)).

The observed behaviour of the BESS and the wind farm while providing FRR corresponded to that expected. Their technical capability to contribute to symmetric and/or asymmetrical FRR was therefore demonstrated.

4.1.2.3 SIMULTANEOUS ACTIVATION OF MULTIPLE FREQUENCY RESERVES

In addition to the tests of individual service provision, another test was performed on the BESS, during which all the three frequency services (FFR, FCR and FRR) were simultaneously activated, to verify whether the storage system was able to provide multiple services to the power system when the needs appear.

For this test, a respective power of 600 kW was reserved for FFR and FCR. Adapted power-frequency regulation laws with narrower regulation ranges than required by the French TSO were defined, as presented in Figure 47(a), in order to be able to trigger different services under real grid frequency events. Moreover, 600 kW of FRR was also provided by respecting the “level N ” setpoints. To ensure the level of SoC during the provision of multiple services, the control law as shown in Figure 47(b) was implemented. A maximum power of 375 kW was dedicated to SoC control, by following a static droop of 37.5 kW/% and a dynamic ramp of 375 kW / 900 s.

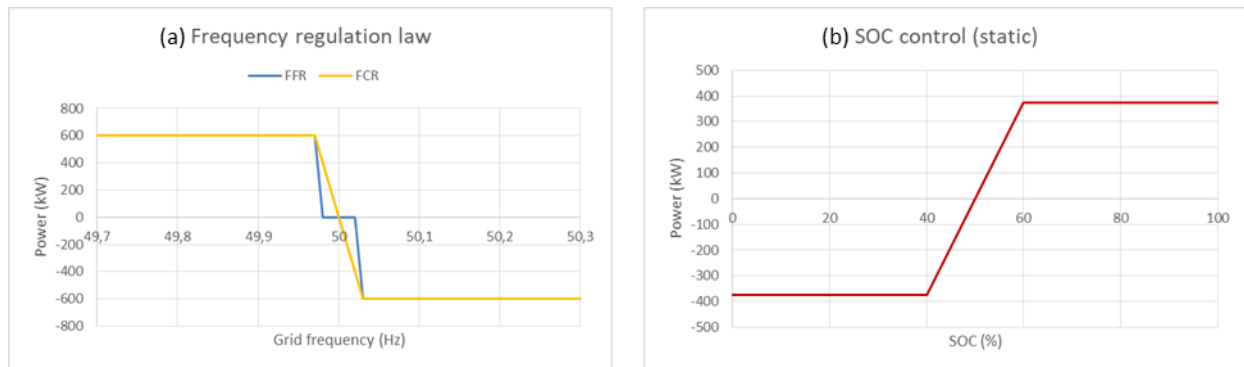


FIGURE 47. CONTROL PARAMETERS AND REGULATION LAW FOR MULTI-SERVICE PROVISION

Figure 48 shows the experimental results of the 1-hour test of the multi-service provision. It was observed that the three frequency services were appropriately activated according to the grid frequency and to the FRR activation signal, in parallel with the SOC control. The resultant power at PoC could be decomposed of the powers dedicated to each service, thanks to the relevant E-SCU controller design (which can output the feedback values of the response of each service). The performance of different active power services can therefore be assessed individually while they were simultaneously provided.

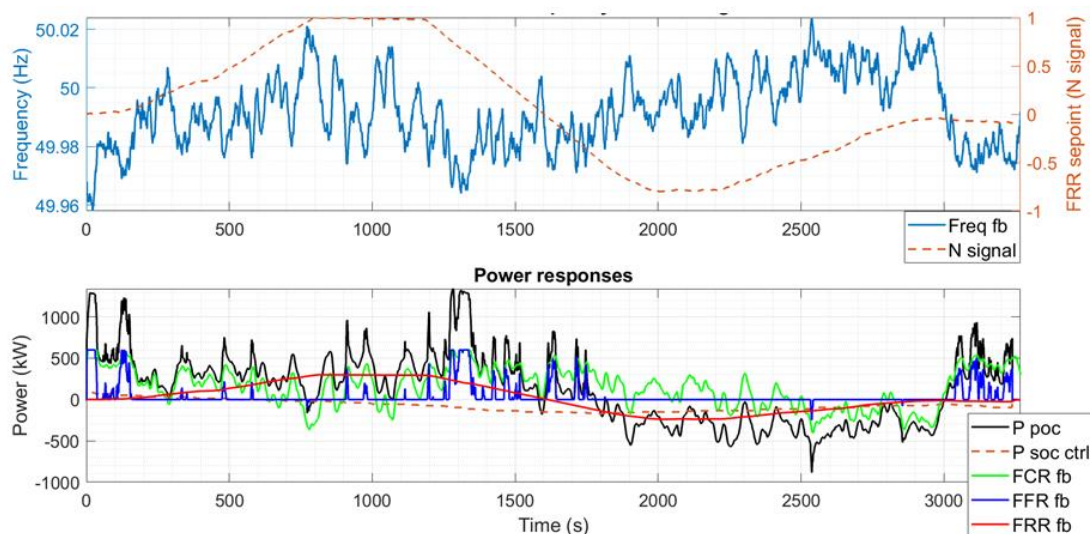


FIGURE 48. MULTI-SERVICE PROVISION BY BESS IN REAL CONDITIONS

The obtained experimental results were satisfactory and showed good performance of various services offered by the BESS. For economic concerns, the similar test was not performed on the wind farm, although the design of the FCU controller also enables the multi-service provision scheme.

4.1.2.4 RAMP RATE CONTROL

The RRC service consists in limiting the power gradients of the total VPP generation by using the storage capacity to reduce renewable power variations. This service was tested by feeding the E-SCU controller a historical profile of *Anglure* wind farm generation as the renewable power input.

Figure 49 shows the BESS response as well as the resultant power output of the VPP when a ramping setpoint was fixed to 20 kW/s (i.e. 1200 kW/min), corresponding to a power variation of 10% of the total installed wind capacity (12 MW) per minute¹⁸.

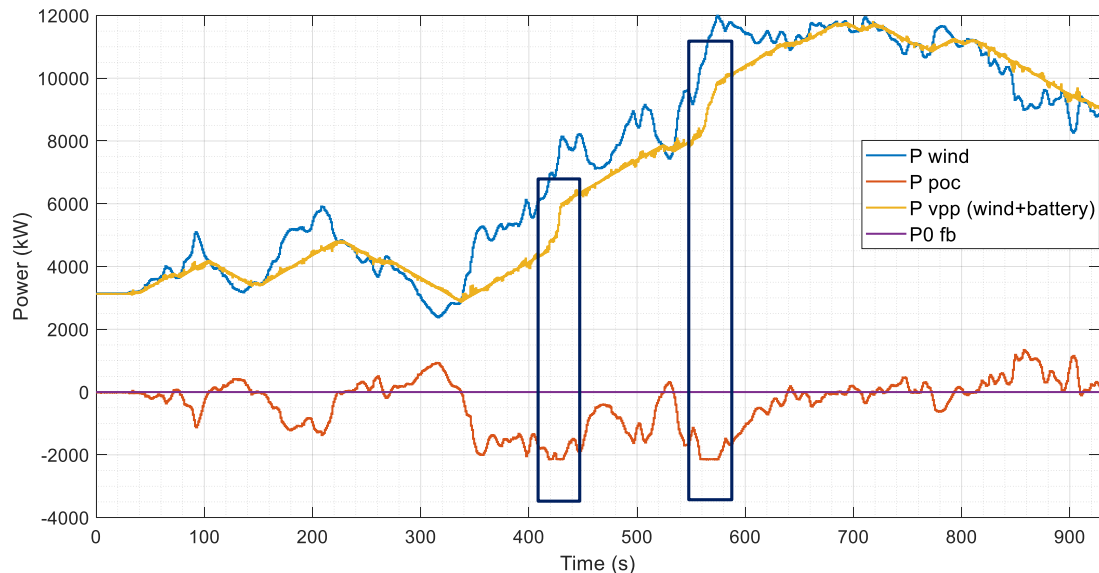


FIGURE 49. RAMP RATE CONTROL OF RENEWABLE GENERATION USING STORAGE

As can be seen from Figure 49, when the wind farm generation ("*P wind*" curve in blue) showed a too important positive (or negative) variation of active power, then the BESS ("*P poc*" curve in red) created a negative (or positive) variation of active power by absorbing (or injecting) the power; the resultant power variation at the VPP level ("*P vpp*" curve in yellow) was therefore contained.

As for FRR delivery, the provision of the RRC service could have important consequences on the storage SoC, especially when a long-lasting duration of the service needs to be ensured. Hence, the activation of a SoC control is essential while performing RRC. However, the dynamics of the additional power due to SoC control could influence the ramp rate of the global generation output. A poorly designed SoC control could therefore lead to unexpected non-compliance with the ramp rate setpoint at the VPP level.

For the EU-SysFlex local tests, a simplified approach of SoC control associated with the RRC service was applied. To respect the global power variation ramp rate (20 kW/s) including SoC control power, a more restricted ramp rate setpoint (15 kW/s) was voluntarily sent to the RRC controller, in order to leave a margin of 5 kW/s dedicated to controlling the SoC. It should be noted that this simple method works correctly by respecting the global ramp rate setpoint, however, it is not the optimal solution and further investigations on this topic will be needed to better design the SoC control strategy for the RRC service.

¹⁸ This ramping setpoint was determined based on the technical feedback of several international public tenders specifying similar requirements, as the specifications of ramping products of this type do not exist in the current French power system.

To assess the performance of the service, the 60-second sliding average of the ramp rate of the wind-storage VPP generation dP/dt_{VPP} was calculated according to Eq. 4:

$$dP/dt_{VPP}(t) = \frac{P_{VPP}(t) - P_{VPP}(t - 60)}{t(t) - t(t - 60)} \quad \text{EQ. 4}$$

Figure 50 shows the calculation outcome for the 15-minute observation period, based on the experimental results illustrated in Figure 49. It is clearly highlighted that the wind generation variation was much reduced thanks to the storage and the ramp rate setpoint RR_{max} (20 kW/s i.e. 1200 kW/min) was globally well respected as long as the BESS does not reach its power and SoC limits (see boxes in Figure 49, which are examples of non-compliance in case of abrupt wind power ramps, while the maximum power capacity of the storage was already used for RRC).

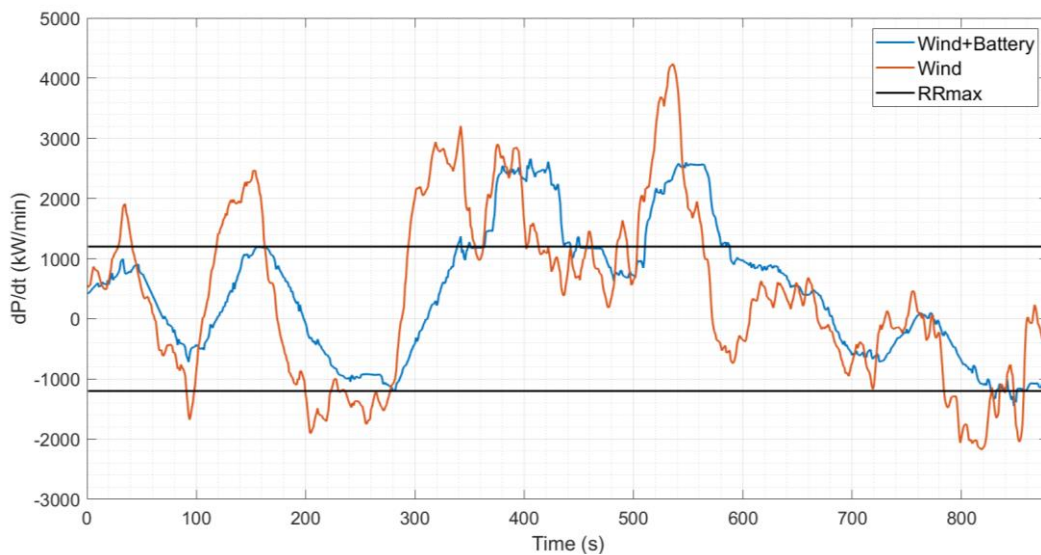


FIGURE 50. RAMP RATE OF VPP V.S. WIND GENERATION ONLY

Table 9 shows further analyses on the percentage of the time when the calculated sliding average of the ramp rate was inside the expected maximum ramp rate during the 15-minute observation period, corresponding to the success rate of the RRC. One can therefore understand that the higher is the success rate, the better is the performance of the service.

Wind only	Wind + battery	Wind + battery with SOC control
50.8 %	71.7 %	83.6 %

TABLE 9. SUCCESS RATE OF RRC IN DIFFERENT CASES

The results confirm the effective contribution of the storage to smooth the renewable generation variation and it can also be found that the activation of the SoC control managed to better ensure the availabilities of the BESS when needed, so as to improve the global performance of the ramp rate control.

4.2 DEMONSTRATION OF THE FULL-CHAIN OF OPERATION

Following the successful trials of the local tests as well as the commissioning of the whole communication and IT platform, the full operation of the VPP was experimented for more than 30 hours, during which all the assets were autonomously managed by the EMS with very limited manual intervention¹⁹.

The direct integration with market interfaces was out of scope, since the VPP approach is not yet compliant with existing market rules in France. During all the tests, the VPP was producing energy and providing frequency containment reserve without real sales in the corresponding markets. Considering the MW size of the VPP, its operation would not have any impact on the security of the French power system. The focus of our tests was to demonstrate the technical feasibility of the proposed VPP approach.

In general, **it was observed that all involved subsystems (forecasting, scheduling, local controls, communication, monitoring, etc.) were very well connected and worked seamlessly.** The autonomous planning, based on renewable generation forecasts, historical market prices and local measures, were generated at each expected time slot, transmitted to local controllers, and executed correctly by each asset.

4.2.1 ILLUSTRATION OF THE VPP OPERATION

The full-chain experiments were performed on 7 days, in order to cover different meteorological and testing conditions, with also a different duration for each test (from 2 hours to 8 hours)²⁰. The test which lasted the longest was achieved on the 22nd of October 2021 and seems the most representative. Hence, the experimental results of this test are presented in detail hereinafter. For the sake of readability, figures based on post-processed experimental data are illustrated, instead of the HMI screenshots which have rather been used for online monitoring during the tests.

4.2.1.1 VPP SCHEDULING

The same process and tools as presented in Section 3.2 were applied to generate the schedules of the day while launching the test on Oct. 22. The deterministic approach was chosen to be used for day-ahead scheduling and intraday rescheduling. Intraday schedules were updated every 30 minutes for all the full-chain experiments.

As depicted in Figure 51, the VPP operating schedules of Oct. 22 were calculated by the OPS with respect to the market prices and to the latest renewable generation forecasts available.

¹⁹ The manual intervention was mainly planned for the preparation and the closing of each test, and was also necessary to stop the tests in case of an emergency, which never occurred during the EU-SysFlex demonstration by the way, and to restart the tests after the emergency removal.

²⁰ As the laboratory of Concept Grid is closed at night, only daytime tests shorter than 8 hours were allowed for the VPP demonstration for security concerns. Note also that the EU-SysFlex tests should be performed when the MV grid was fully available (without any other tests programmed at the same voltage level) to limit interference, which could also reduce the time duration of the tests. However, the successful demonstration of the suggested VPP approach is not undermined by these minor technical constraints.

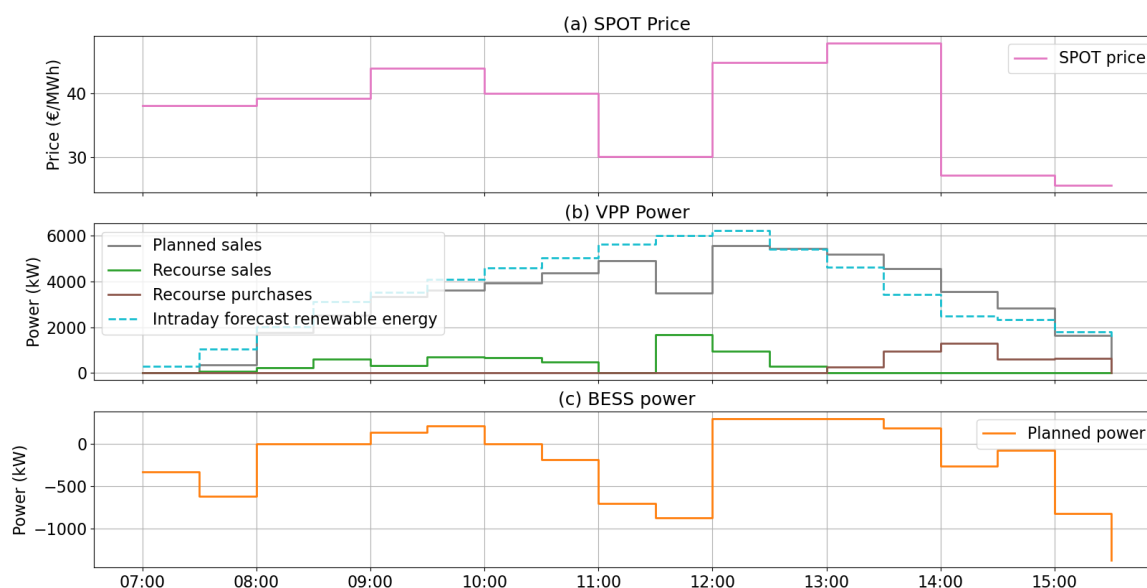


FIGURE 51. VPP SCHEDULING ON OCT. 22, 2021

For an optimal energy arbitrage of the VPP, the OPS generally tends to discharge the battery when the Spot prices are high (if the day-ahead energy commitment cannot be fulfilled at this moment, in case of surplus, the excess energy will be sold anyway at high prices; and in case of shortage, fewer recourse purchases will be necessary as the battery is injecting power). Similarly, the OPS tends to charge the battery when the Spot prices are low (if the day-ahead energy commitment cannot be fulfilled at this moment, in case of surplus, it will be better to charge the battery with the excess renewable energy and to discharge when the prices go higher; and in case of shortage, recourse purchases from the market will be less penalized at lower prices).

As expected, it can be seen from Figure 51 that on the day of the test, the OPS decided to charge the battery with renewable generation when the Spot price was low at 11:00. and discharge power when the price was higher from 12:00 to 14:00 (Figure 51(a) and (c)).

Regarding the FCR provision, in general the OPS chooses to allocate downward reserve on the wind farm to avoid costly renewable energy curtailment, and optimizes the distribution of the total amount of FCR on both the storage and the wind farm to maintain the symmetry of the reserve provision at all times. During the 8-hour test on Oct. 22, the FCR price was interesting enough and the OPS has planned to provide 1.5 MW²¹ of symmetric FCR at the VPP level.

Figure 52 shows the optimal FCR allocation within the VPP. As expected, upward reserve was mainly assured by the BESS for the whole day and very temporarily by the wind. Downward reserve was first provided by the BESS in

²¹ As explained in Footnote 7, according to the ENTSO-E rules, a battery of 2 MW is allowed to provide a maximum of 1.6 MW of FCR, while keeping 25% of its full capacity for the correct management of its energy reservoir facing extended frequency deviations of 50 mHz. For the full-chain experiment on Oct. 22, there was a material constraint in the battery container, which led to a lower full power capacity of 1.875 MW. Therefore, it was decided to use 1.5MW as the maximum value of FCR on the battery, based on the above-mentioned sizing criteria. For this reason, it was decided by the OPS to provide 1.5 MW of symmetric FCR at most. However, if the FCR market price had been sufficiently higher than the Spot market price, the optimizer would have decided to provide more than 1.5MW of FCR with the VPP, meaning that additional upward reserve would have been allocated on the wind farm.

the morning where the renewable generation was supposed to be low according to the forecasts, and mostly allocated on the wind farm starting from 11:00, so as to leave sufficient power and energy margin on the BESS for energy arbitrage.

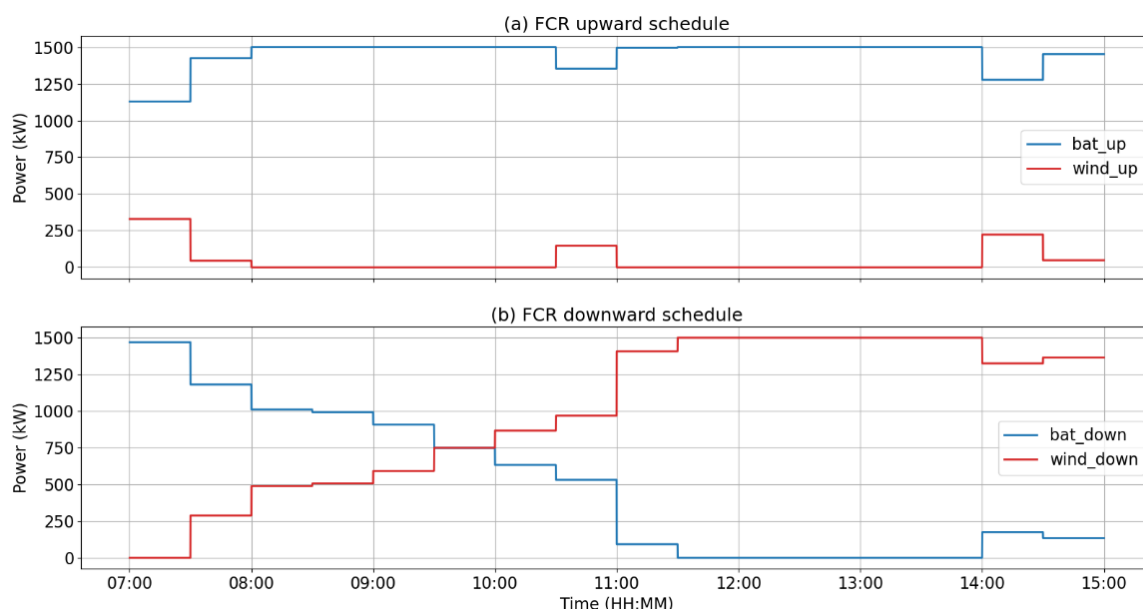


FIGURE 52. DISTRIBUTION OF THE FCR ON THE BATTERY AND THE WIND FARM

Once the generation of the operational planning for the day is presented, in the following sections will be illustrated the real-time behaviour of the different assets to verify whether the VPP was correctly operated with respect to the defined planning.

4.2.1.2 REAL-TIME BEHAVIOUR OF THE VPP

As illustrated in Figure 53(a), the actual power of the VPP corresponds to the sum of the BESS power and the power output by wind and PV generators. Large power fluctuations over noon and at the beginning of the afternoon came from important power variations of the PV generation, probably due to moving clouds, over the same period.

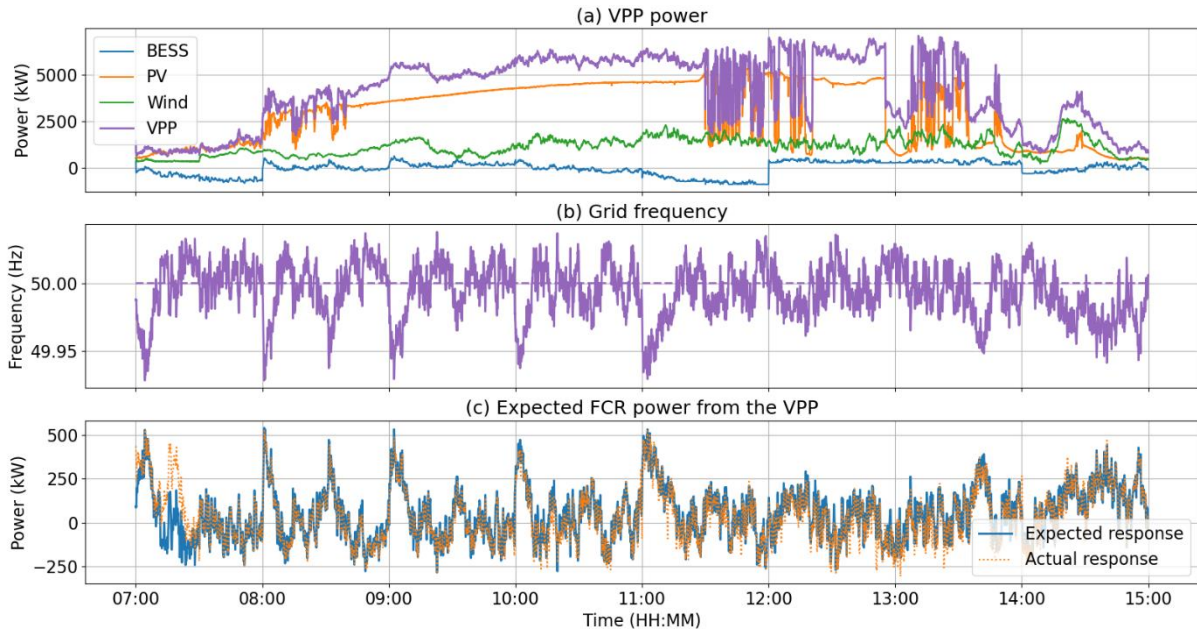


FIGURE 53. ACTUAL POWER OF THE VPP AND EXPECTED FCR RESPONSE

The 1500 kW of FCR should be fully delivered to the grid for a frequency deviation of ± 200 mHz, meaning that the power frequency droop of the VPP ($k_{VPP_contracted}$) was equal to 7500 kW/Hz. Once the grid frequency f was measured (Figure 53(b)), the expected "ideal" FCR response $P_{FCR_VPP_expected}$ can therefore be deduced (Figure 53(c)) following the FCR regulation law:

$$P_{FCR_VPP_expected}(t) = k_{VPP_contracted} \cdot (50 - f(t)) \quad \text{EQ. 5}$$

It can be observed that the actual FCR response provided by the VPP was quite close to that expected with occasional deviations, to a greater or lesser extent ((Figure 53(c)), which will be further analysed by inspecting the detailed behaviour of individual resources.

4.2.1.3 DYNAMIC BEHAVIOUR OF THE BESS

Figure 54 shows the total power of the battery (a) and its SoC (b). The total power corresponds to the sum of the baseline power (P_{0_BESS}) scheduled by the OPS for energy arbitrage on SPOT market and the power dedicated to FCR provision, which oscillated around the baseline power as a function of the grid frequency (Figure 53(b)).

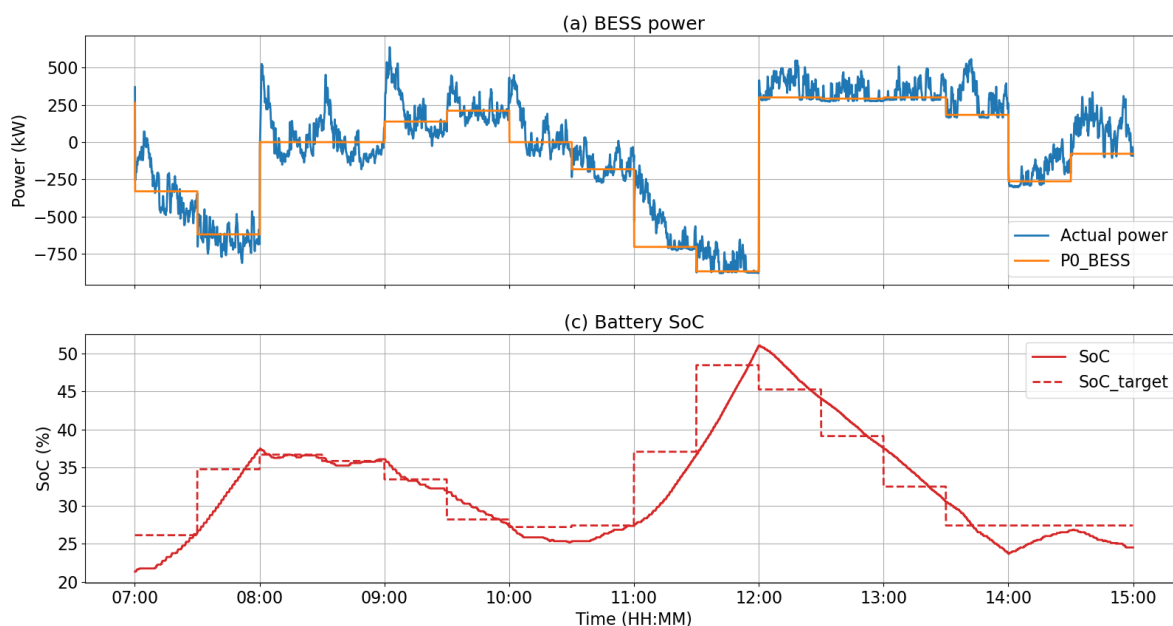


FIGURE 54. BATTERY POWER AND SOC

The scheduler internally computes a SoC reference that is supposed to be reached at the end of each time step if the battery follows the setpoint. This SoC is named « *SoC_target* » in Figure 54(c). The differences between the final SoC measured and its « target » value came mainly from the modelling errors due to the simplified consideration of the BESS energy loss by the scheduler, and/or from extended frequency deviations (e.g.: between 13:30 and 14:00).

Figure 55 provides a zoom on the FCR response of the BESS for one hour. It can be clearly seen that the battery only responded to underfrequency events (when the grid frequency is below 50 Hz)), as according to the FCR planning, only upward reserve was supposed to be allocated on the BESS during this hour (cf. Figure 52), which is the case observed here.

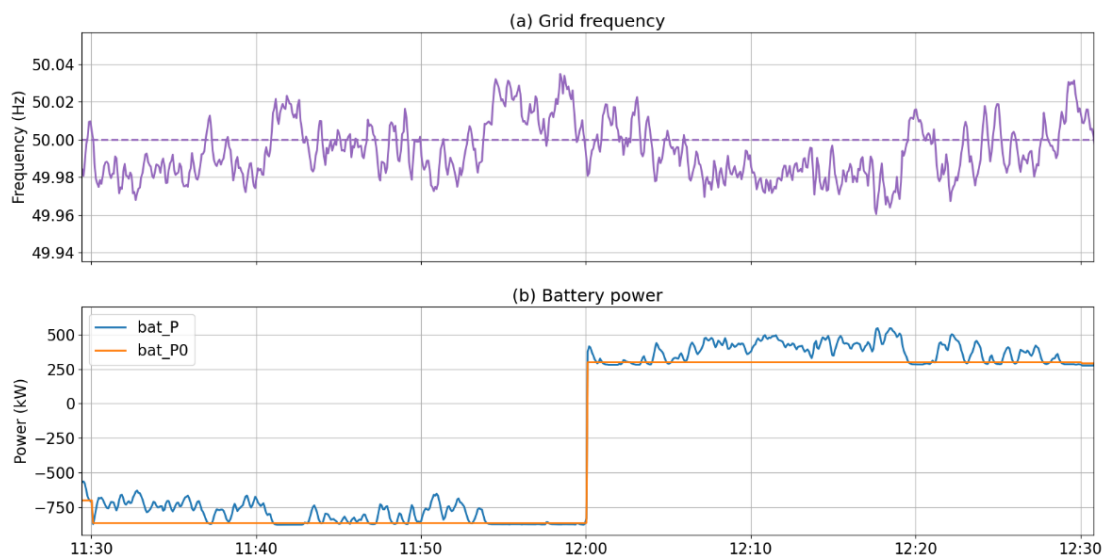


FIGURE 55. ZOOM ON THE FCR PROVISION BY THE BATTERY

The "ideal" FCR response that were expected to be provided by the BESS can be deduced by applying Eq. 6.

$$P_{FCR_BESS_expected} = k_{BESS} \cdot (50 - f) \quad \text{EQ. 6}$$

With:

k_{BESS} : Equivalent BESS FCR gain, corresponding to the delivery of the full FCR allocated on the BESS for a frequency deviation of ± 200 mHz.

The assessed actual FCR response from the BESS can be extracted from its total power measured at the PoC (P_{mes_BESS}) by "removing" the baseline power (P_{0_BESS}):

$$P_{FCR_BESS_assessed} = P_{mes_BESS} - P_{0_BESS} \quad \text{EQ. 7}$$

Figure 56 illustrates the difference between the expected and the assessed effective FCR contribution from the battery by comparing $P_{FCR_BESS_expected}$ and $P_{FCR_BESS_assessed}$ for the whole test. The absolute mean power difference was equal to 13.8 kW and the maximum power difference amounted to 35 kW.

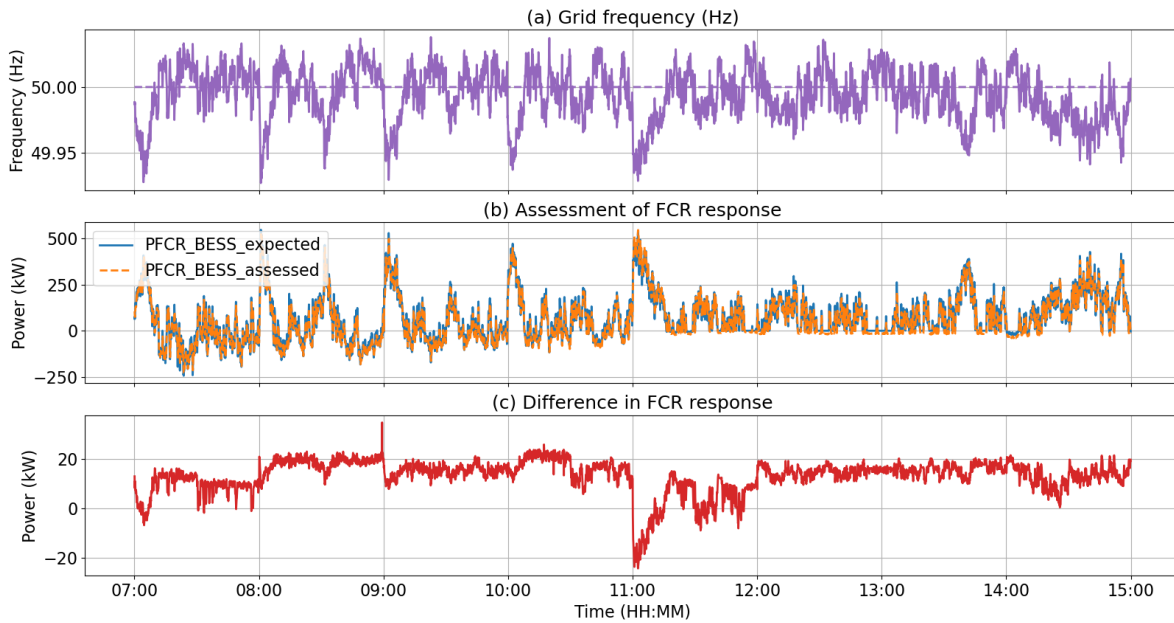


FIGURE 56. EXPECTED AND ASSESSED FCR RESPONSE FROM THE BESS

Indeed, it was generally found that the E-SCU power controller design was based on an open-loop control, resulting in slight active and reactive power differences between the power measured at the PoC and its setpoint, which correspond to the power losses in the auxiliaries and in the MV transformer. Due to this fact, there were always small gaps between the actual and the expected FCR responses from the battery. Although the power errors were relatively low and were not primarily responsible for the underperformance of the global VPP, the E-SCU controller can still be further enhanced by applying a closed-loop control to respect more precisely the received active power references.

4.2.1.4 DYNAMIC BEHAVIOUR OF THE WIND FARM

The estimated available active power (AAP) and the actual power output of the wind farm during the day of the test are plotted in Figure 57. When only downward reserve was provided, these two curves could be quite close and sometimes it did not seem obvious to visualize the differences, as only frequency excursions higher than 50 Hz would make the wind farm reduce a certain amount of its generation from the AAP. However, the hours when the wind farm provided upward FCR are remarkable (e.g.: 07:00-08:00, 10:30-11:00, and 14:00-14:30, as shown in Figure 52(a)), as a power gap was constantly maintained between the AAP and the active power measured for reserve constitution.

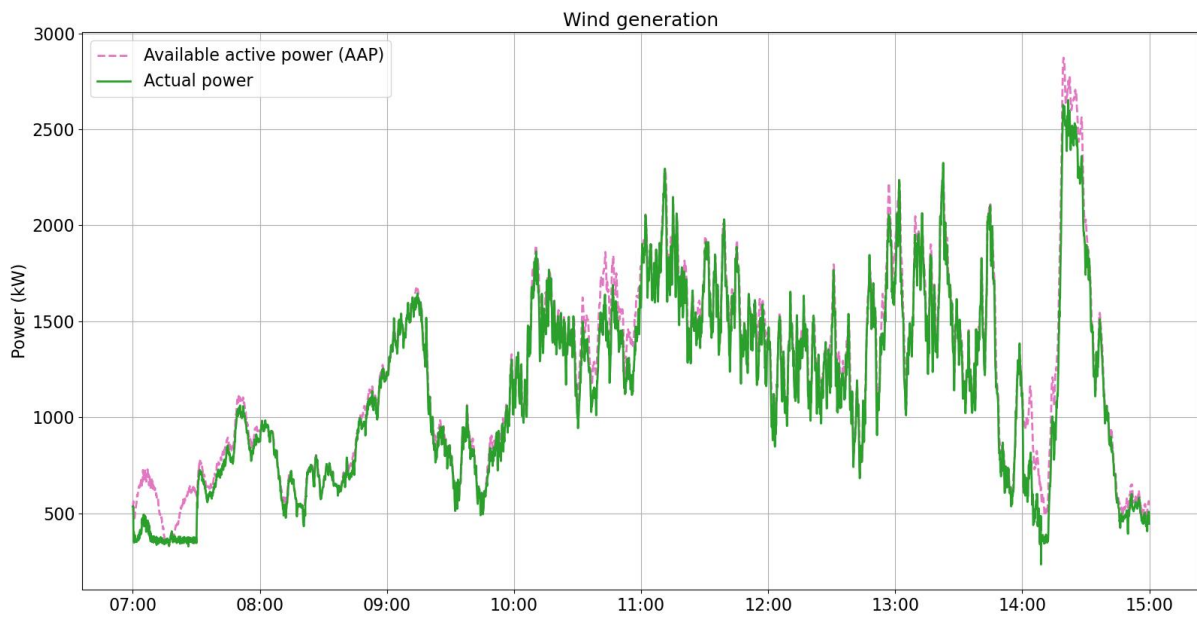


FIGURE 57. AVAILABLE WIND POWER AND ACTUAL GENERATION

Similarly, as for the battery, the expected wind FCR response can also be calculated according to the measured grid frequency by Eq. 8:

$$P_{FCR_wind_expected} = k_{wind} \cdot (50 - f) \quad \text{EQ. 8}$$

With:

K_{wind} : Equivalent wind FCR gain, corresponding to the delivery of the full FCR allocated on the wind farm for a frequency deviation of ± 200 mHz.

As explained in Section 4.1.1.1, the baseline operating point of the wind farm corresponds to its maximum available power minus the quantity of the allocated upward reserve. Then the effective wind FCR response can be assessed by applying the following equation:

$$\begin{aligned} P_{FCR_wind_assessed} &= P_{mes_wind} - P_{0_wind} \\ &= P_{mes_wind} - (P_{AAP_est} - P_{FCR_up_wind}) \end{aligned} \quad \text{EQ. 9}$$

The expected FCR contribution from the wind farm was broadly negative (Figure 58(b)), since during most of the time only downward reserve was provided. In another word, the wind farm was supposed to regulate its power output in response to the frequencies above 50 Hz. Figure 58 illustrates the power difference between the expected and the assessed wind FCR response. The observed absolute mean power difference was equal to 36.4 kW and the maximum value reached 337 kW (Figure 58(c)).

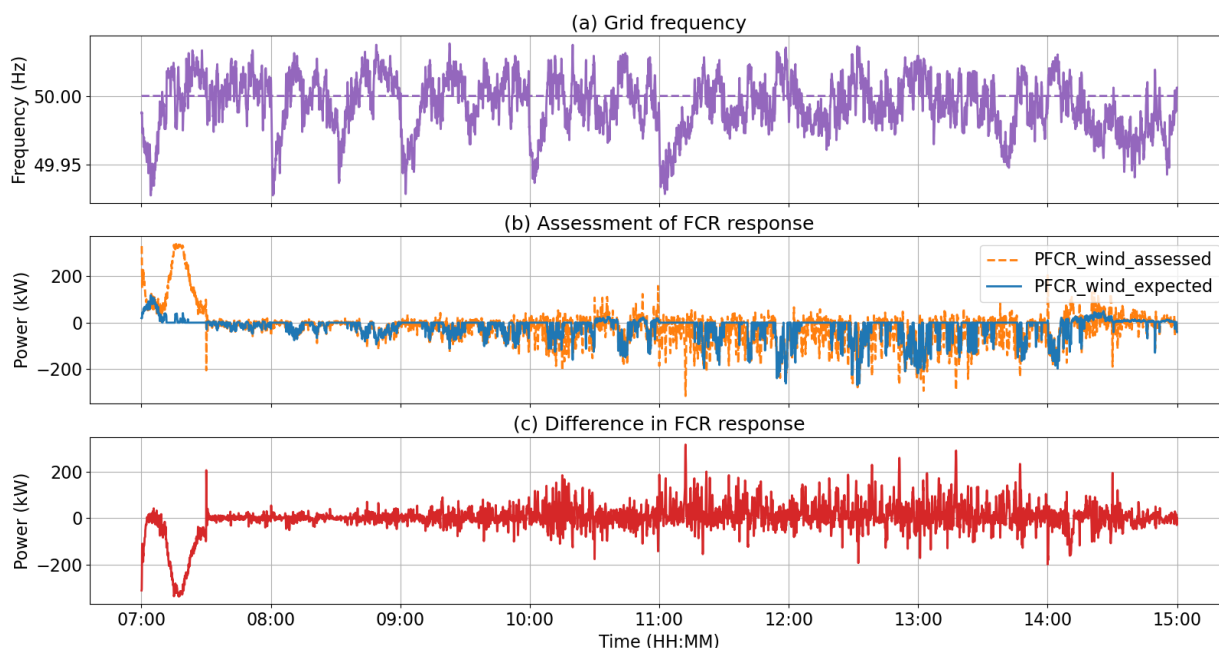


FIGURE 58. EXPECTED AND ASSESSED FCR RESPONSE FROM THE WIND FARM

The highest power differences occurred in the first 30-minute period of the test, during which the OPS had decided to allocate 300 kW of upward FCR on the wind farm (cf. Figure 52), meaning that wind generation had to be decreased by 300 kW for reserve constitution. This day-ahead decision had been made based on the wind forecasts and had been supposed to be optimal. However, in real time, there was much less wind than forecasted. Although the wind farm was already operated at its minimal power (360 kW for the *Anglure* wind farm) and it was technically no longer possible to further lowers the generation, the reserve provided was still far from the expected level (cf. Figure 57 at 7:30).

Another issue which could also cause large deviations of the wind FCR response is related to the estimation error of the AAP, as previously explained in Section 4.1.1.3. A 15-minute zoom is illustrated in Figure 59 to highlight the impact of overestimation. During this period, the wind farm only provided downward reserve (Figure 52) and the grid frequency remained below 50 Hz (Figure 59(d)), i.e. the wind farm was not supposed to decrease its power output. However, the overestimation of the wind AAP could lead to power gaps between the estimated setpoint and the actual power (Figure 59(a)) in the direction of upward frequency regulation, as if the farm participated in upward FCR, and therefore, resulted in power differences between the assessed and the expected FCR response (Figure 59(b) and (c)).

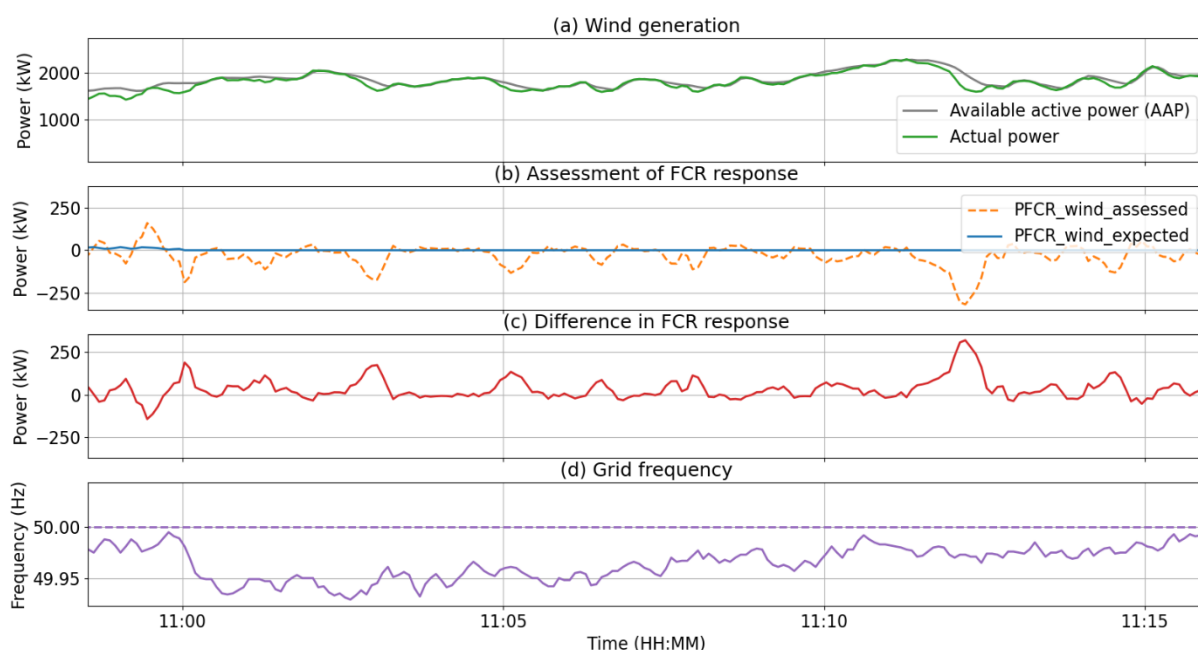


FIGURE 59. IMPACT OF THE OVERESTIMATION OF THE WIND AAP ON FCR RESPONSE

In addition to the accuracy of the forecasts, the quality of the AAP estimation continuously influences the “correctness” of the FCR constitution and delivery, while wind generation participates in this service, and is key to enhance the performance of the FCR provision by the wind farm and by the VPP.

4.2.2 ASSESSMENT OF TECHNICAL KPIS

To further assess the dynamic behavior of the VPP when it was completely operated, three technical KPIS have been defined: two of them for measuring the compliance of the frequency service provided by the VPP with the requirements of the TSO; and one for evaluating the reliability of the IEC-61850-based communication platform. These KPIS were assessed by post-processing the experimental results of all 7 full-chain tests (with a total duration of 31 hours).

4.2.2.1 FCR GAIN ASSESSMENT

The first technical KPI (KPI n°4) is dedicated to verifying whether the actual gain of the VPP while offering the FCR service is compliant with the requirement of the TSO (Table 10), and has been assessed by applying the same approach as detailed in Section 4.1.1.3.

In practice, the French TSO RTE verifies the quality of the FCR service provided in two phases. In the qualification phase aiming at the certification of assets for FCR provision, the tests consist in verifying their responses to the frequency step setpoints (± 50 mHz and ± 200 mHz) for a 15-minute duration as described in the technical reference document [12]. To obtain the FCR certification, the full reserve must be activated in less than 30 seconds (full activation delay criterion) and held for at least 15 minutes if the frequency deviation remains at 200 mHz. For the French VPP, these criterion have been partially verified through the local tests focusing on the FCR provided by individual resources (cf. Section 4.1.1). It should be noted that the holding time of 15 minutes, which

can be easily assured by conventional power plants and well-sized batteries, seems complicated to be guaranteed for the reserve provided by renewables.

In the second performance measurement phase, the TSO carries out a continuous quality assessment of the service over the FCR contract lifetime based on the monitoring data. As the tests performed in EU-SysFlex cover the FCR contribution in an operational mode based on real grid frequency, the following analyses refer rather to this performance measurement phase.

KPI n°4			
KPI name	Compliance of the assessed FCR gain with the TSO's requirement	KPI ID	CSP
Main objective	Evaluate the performance of the FCR service provided by the VPP based on the requirements specified by the French TSO (RTE) in the current grid code.		
KPI Description	<p>According to the current rules of RTE, if one asset provides FCR with an actual gain lower than 20% of the contracted value, for more than 10% of the monitored period, the service is then considered as partially unavailable. In other words, to comply with RTE's requirements, the assessed FCR gain must mostly remain above 80% of the contracted theoretical value. Otherwise, the participating asset will be warned, and penalties will be applied if no corrective action is taken.</p> <p>Although the current market and technical requirements are not necessarily appropriate for assessing the reserve provided by renewables and may need to be adapted in the future, due to lack of references, this KPI assesses the "performance" of the VPPs' FCR by applying the current requirements.</p>		
Unit	%		
Formula	$CSP[\%] = \frac{T_{compliant}}{T_{compliant} + T_{non-compliant}} \times 100\%$ <p>Where:</p> <p>$T_{compliant}$ [min] is the time duration in which the FCR provided by the VPP is compliant with the TSO's current requirement in terms of gain.</p> <p>$T_{non-compliant}$ [min] is the time duration in which the FCR provided by the VPP is not compliant with the TSO's current requirement in terms of gain.</p>		
Target value	As close to 90% as possible		

TABLE 10. KPI N°4: COMPLIANCE OF THE ASSESSED FCR GAIN TO THE TSO'S REQUIREMENT

Similar as for wind generation, the key to allow the assessment of the actual FCR gain of the VPP is to "know" its baseline operating power (P_{0_VPP}). This value can be calculated by adding up the baseline power of the BESS and

that of the wind farm, as well as the power output of the PV farm (which did not offer any reserve and produced its maximum power available), as shown in Eq. 10:

$$P_{0_VPP} = P_{0_BESS} + P_{AAP_est} - P_{FCR_up_wind} + P_{mes_PV} \quad \text{EQ. 10}$$

The objective of the FCR gain assessment is therefore to estimate the actual droop (k_{VPP_actual}) of the following equation:

$$P_{mes_VPP} = P_{0_VPP} + k_{VPP_actual} \cdot (50 - f) \quad \text{EQ. 11}$$

With:

$$P_{mes_VPP} = P_{mes_BESS} + P_{mes_wind} + P_{mes_PV} \quad \text{EQ. 12}$$

The 5-second power and frequency measures were used to estimate the droop (k_{VPP_actual}) for each 10-minute period through the least-square method. As an example, Figure 60 depicts the result of the FCR gain (in *per unit*) for the illustrated test performed on Oct. 22. It can be observed that the assessed droop was lower than 0.8 p.u. 31% of the time, meaning that the FCR performance of this test was compliant for 69% of the total duration.

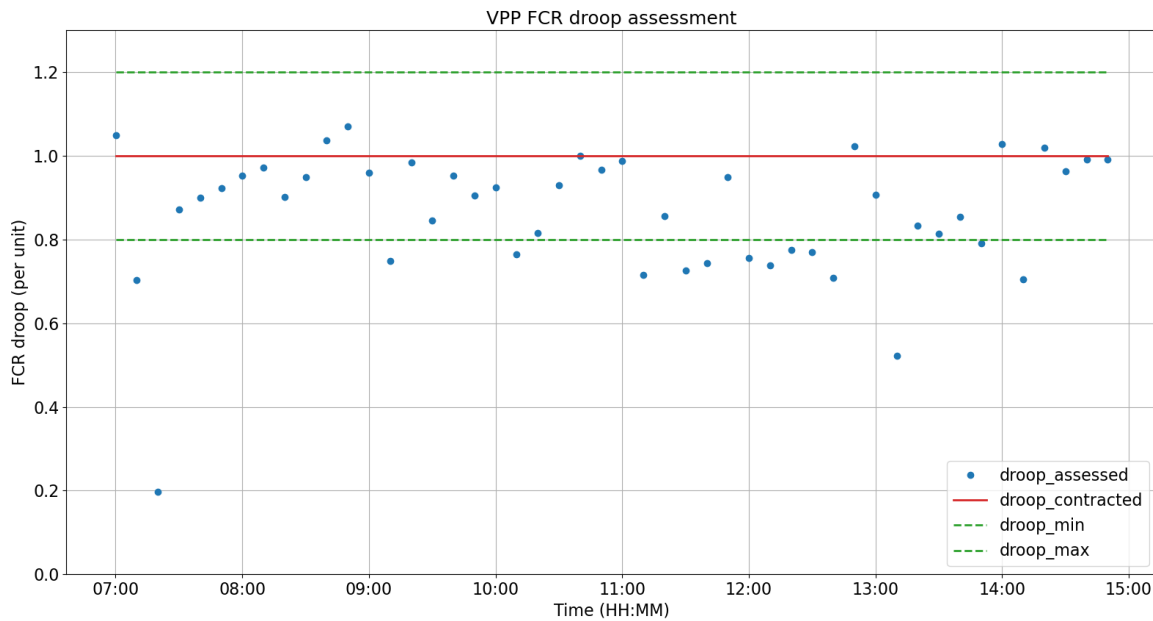


FIGURE 60. FCR GAIN ASSESSMENT FOR THE TEST ON OCT. 22

Table 11 gives an overview of the percentage of time during which the assessed FCR gain of the VPP conformed to the required quality level (CSP), evaluated for each test. The overall CSP for the total duration of all tests is about 53%, lower than the expected performance (90%).

Test n°	Date	Duration	CSP
1	Oct. 20, 2021	5h	59%
2	Oct. 21, 2021	1h45	10%
3	Oct. 22, 2021	8h	69%
4	Oct. 28, 2021	7h	43%
5	Oct. 29, 2021	2h15	69%
6	Dec. 9, 2021	4h30	44%
7	Dec. 9, 2021	2h30	50%
Assessed CSP for the total duration of the tests			53%

TABLE 11. ASSESSED PERCENTAGE OF TIME OF "COMPLIANT FCR" (IN TERMS OF FCR GAIN)

The analysis result of this KPI is not surprising nor as negative as it might be understood by just comparing numbers. Indeed, some of the technical reasons for which the actual FCR responses of the VPP were less efficient than expected have been illustrated in the previous paragraph through concrete examples and suggestions for improvements can also be identified for each issue:

- The first observed problem is the power difference between the setpoint and the actual power of the BESS due to the open-loop control of the storage controller. This problem is not the main reason for the underperformance of the FCR service provided and can be easily solved for future industrial projects by implementing a closed-loop control.
- The second issue concerns the lack of full-capacity reserve allocated on the wind farm. This happens when less wind is available in real time, due to forecast errors, to enable the full delivery of the scheduled reserve. The estimation of the FCR droop during these moments result certainly in very poor performance. **Improving forecast quality will undoubtedly help reduce the risk of lack of reserve with respect to the FCR schedules.** Another solution consists in taking into consideration an additional power margin for wind reserve constitution while performing day-ahead scheduling (e.g.: by considering a certain amount of power above which reserve distribution can be allowed on the wind farm or by reserving more wind power than the declared reserve). However, this will lead to the risk of missing optimal economic opportunities and/or result in more wind energy loss.
- The third issue affecting the performance of the provided FCR response is related to the quality of the estimation of wind available active power at every second, which is crucial for ensuring the proper amount of reserve that should be delivered. It has been found that **the accuracy of the current AAP estimator should still be further enhanced.** Apparently, manufacturers know how to improve it (e.g.: by modelling more precisely the aerodynamics and the wave effect at the wind farm level), but need more clear incentives from the markets to proceed. It is also recommended that **the definition of the wind "available active power" and the qualification process of the AAP estimation should be standardized by normative bodies in agreement with SOs, regulators, producers and manufacturers,** as the knowledge of

the AAP is essential to allow the performance monitoring of the FCR response provided by wind generation.

- Last but not least, the assessment has been performed by analysing the experimental results of a VPP demonstration carried out at a reduced scale. **The precision of the forecasts and the AAP estimation will be considerably improved for a large-scale VPP** aggregating several well-dispersed renewable generation systems. Consequently, **the performance of the FCR response procured from such a VPP will be largely enhanced at the power system perimeter.**

Another noteworthy point regards the impact of the symmetry of wind reserve on the performance of the FCR service. It is generally found that when a symmetric reserve is provided by the wind farm, the impact of the AAP estimation errors seems to be reduced, leading to an improved quality of the service provided. As an example, Figure 61 depicts the power differences between the actual and the "ideal" FCR response, assessed for the 5-hour test performed on Oct. 20. During this test, the OPS decided to allocate downward reserve on the wind farm during the whole period and upward reserve only for the first 30 minutes. It can be noticed that the average FCR regulation errors were much lower in the first half hour than in the remaining testing time. Indeed, while upward reserve is provided, i.e. wind power is curtailed from its AAP, a power margin is "voluntarily" taken with respect to the estimated AAP, which hedges against the unexpected power deviations due to estimation errors. In a nutshell, **the FCR performance of a wind farm in terms of the regulation gain seems to be higher when it provides symmetric reserve rather than only downward reserve. However, this results inevitably in more energy losses for reserve constitution.**

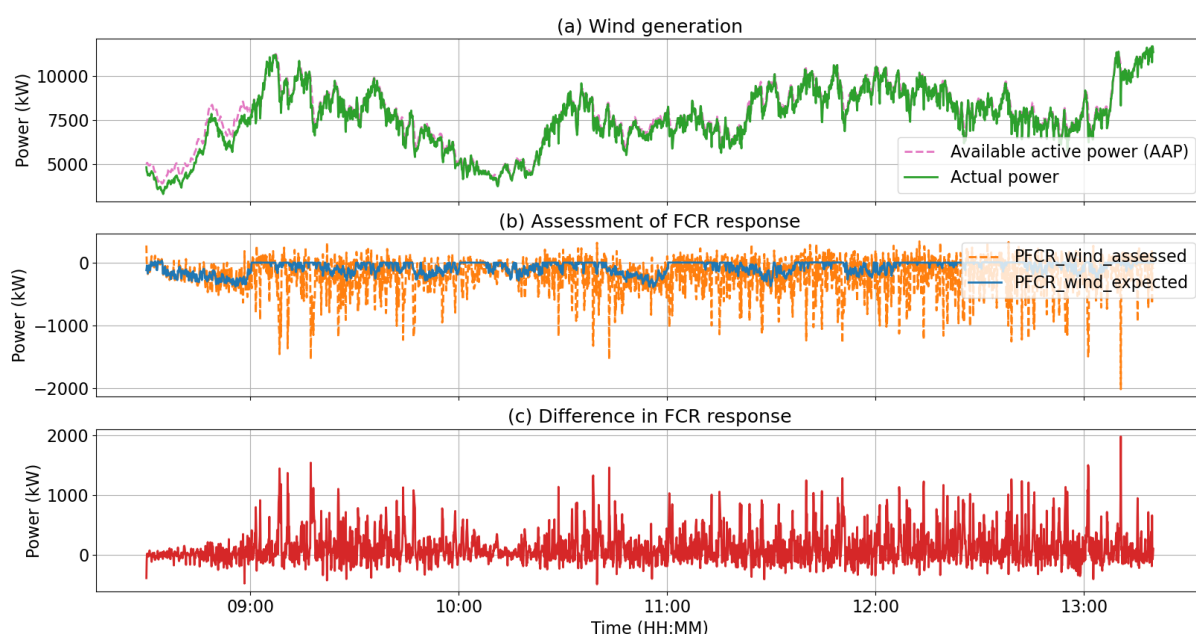


FIGURE 61. COMPARISON OF THE ASSESSED AND EXPECTED WIND FCR RESPONSE FOR THE TEST ON OCT. 20

Moreover, it is important to point out that due to its variable (and unpredictable) nature, the frequency reserve provided by renewable generation could not be as "accurate" as that offered by a battery storage. The actual FCR

response of the VPP as a function of the grid frequency, for the test performed on Oct. 22, is illustrated in Figure 62. One can observe that the underfrequency responses (corresponding to the delivery of upward reserve mainly allocated on the BESS) complied more precisely with the expected regulation than the overfrequency responses (corresponding to the delivery of downward reserve mainly provided by the wind farm). Hence, it can be concluded that **the use of the storage capacity enhances the overall technical performance of the frequency service procured from the VPP.**

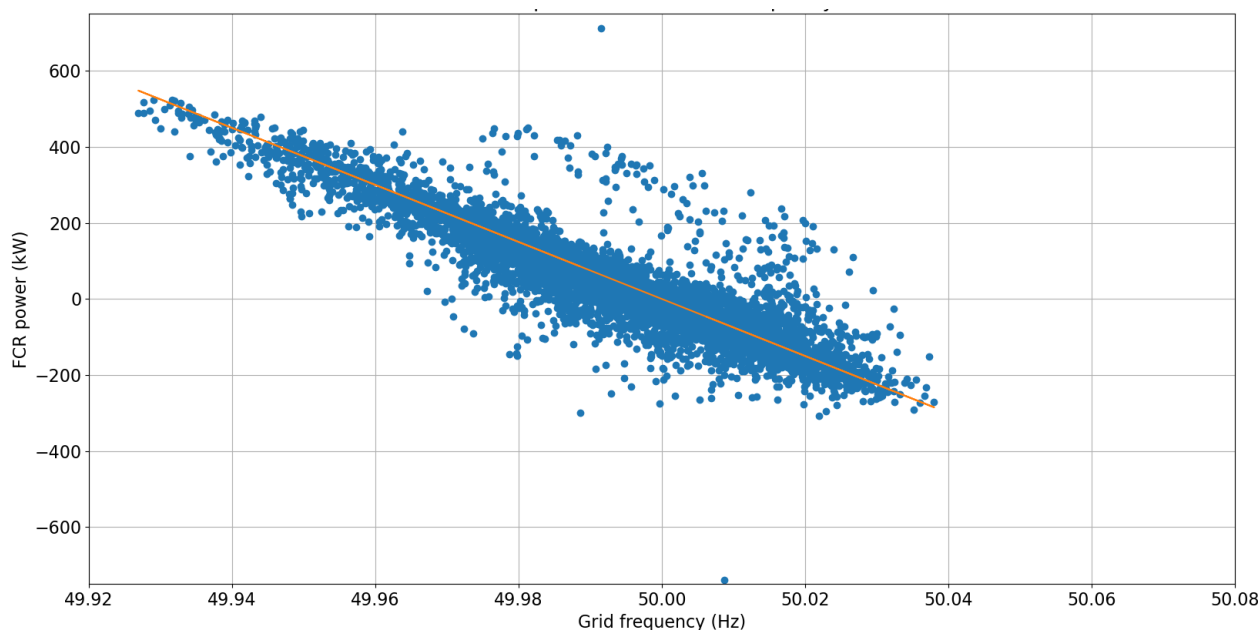


FIGURE 62. FCR RESPONSE OF THE VPP AS A FUNCTION OF GRID FREQUENCY (TEST ON OCT. 22)

Finally, note also that the method applied to assess the actual gain of the FCR response was originally designed and employed by the TSO for measuring the compliance of conventional power plants. It is therefore questionable whether this method is appropriate to assess the effectiveness of the FCR provided by variable resources. Further investigations with TSOs on this subject would still be necessary. In any case, it is important to share publicly the detailed method of periodic performance assessment for new technologies willing to participate in the FCR market.

4.2.2.2 AVAILABILITY OF RESERVE PROVISION

This KPI aims at assessing whether the committed FCR of the VPP is fully available when the extreme values of the grid frequency are reached during the frequency regulation (Table 12). Note that the symmetry of the product and the minimum commitment duration for the participation in FCR have been guaranteed in the scheduling phase. In addition, the BESS is sufficiently sized to ensure the full delivery of its allocated reserve, for a minimum duration of 15 minutes, thanks also to the correctly tuned SoC control. Therefore, the assessment of this KPI consists in measuring the “availability” of the FCR allocated on the wind farm.

KPI n°5			
KPI name	Availability of the reserved power capacity for FCR provision	KPI ID	ARP
Main objective	Evaluate the availability of the FCR reserve that should be provided by the VPP in each commitment period.		
KPI Description	The current market rules require that FCR provision has to be committed a day ahead for at least a duration of 4 hours and in a symmetric form. In practice, on the very day, the FCR is rarely fully delivered and the mobilized reserve depends on the grid frequency. However, the committed reserve is deemed "available" only when it can be entirely delivered if extreme frequencies occur. In the context of the French VPP, the availability of the FCR could be affected by the variability of wind generation, notably when the reserve is allocated on this resource.		
Unit	%		
Formula	$ARP[\%] = \frac{TPS}{TPS + TRS} \times 100\%$ <p>Where:</p> <p><i>TPS</i> [min] is the time duration in which the FCR provided by the VPP is considered as fully "available".</p> <p><i>TRS</i> [min] is the time duration in which the FCR provided by the VPP cannot be considered as fully "available" for different technical reasons.</p>		
Target value	as close to 100% as possible		

TABLE 12. KPI N°5: AVAILABILITY OF THE RESERVED POWER CAPACITY FOR FCR PROVISION

Indeed, at every time when the FCR service is committed and a part of (or the whole) power reserve is decided to be allocated on the wind farm according to the operational schedule, it is necessary to verify if the total amount of reserve can be properly delivered within the allowed technical operating ranges of the wind farm, especially when it comes to downward reserve (in case of upward reserve, a dedicated amount of power should be first subtracted from the estimated AAP and the wind farm can technically increase its power output to the AAP level when the frequency decreases to the lower band of the FCR regulation). In another word, the reserve provided by the wind farm (and by the VPP) is deemed "available" when the acceptable minimum power²² (P_{min_wind}) is not reached, in case the whole downward reserve should be released facing the largest frequency deviation in the regulation band (+200 mHz, i.e. at $f = 50.2$ Hz).

²² Note that a full-converter-based wind turbine can technically curtail its power till zero kW, however, a minimum active power that is allowed to be produced at the wind farm level, generally around only a few percent, has been defined in the parameter settings of the wind controller, which is a prevention of possible shut down of wind turbines due to too low setpoints. The actual value of this minimum power allowed depends a lot on the weather condition and the duration of curtailment. For example, if the weather is humid and cold and the curtailment takes a long time, then the turbines might go into the preventive generator heating.

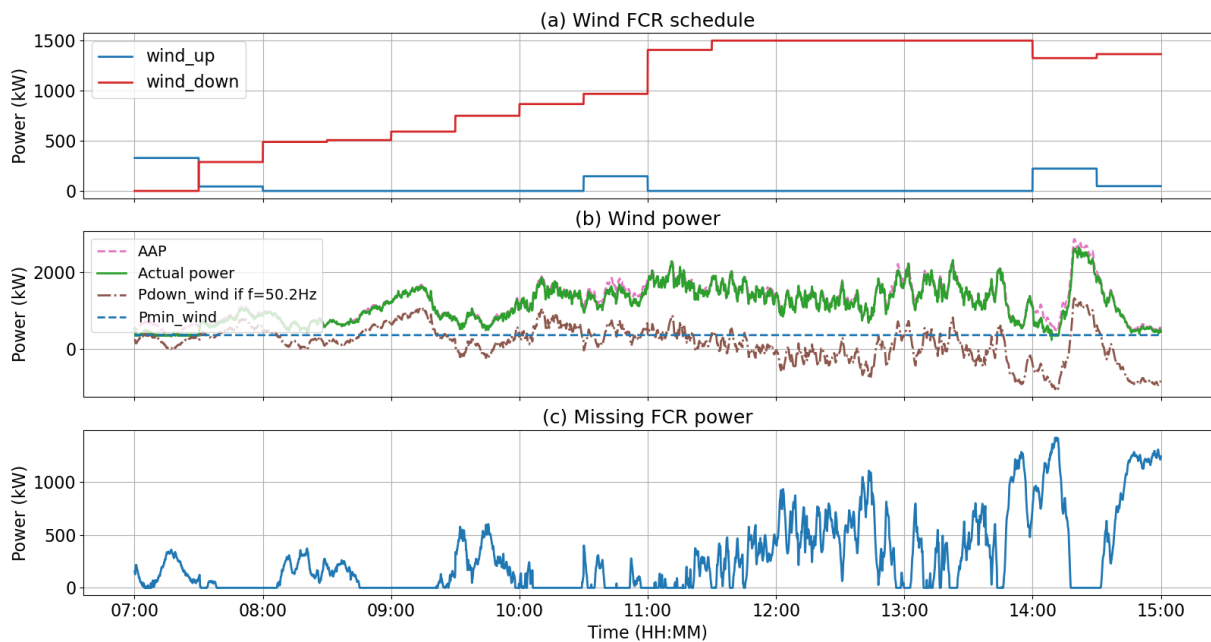
The operating point of the wind farm (P_{down_wind}) while the allocated downward reserve ($P_{FCR_down_wind}$) is fully delivered can be calculated according to Eq. 13. The quantity of upward reserve ($P_{FCR_up_wind}$) turns out to be zero if only downward reserve is provided.

$$P_{down_wind} = P_{AAP_est} - P_{FCR_up_wind} - P_{FCR_down_wind} \quad \text{EQ. 13}$$

Therefore, the availability of the wind reserve is ensured if P_{wind_down} remains higher than P_{min_wind} . Otherwise, the quantity of the "missing" FCR (which represents the amount of reserve not being available if the frequency reaches 50.2 Hz) can be deduced by applying Eq. 14.

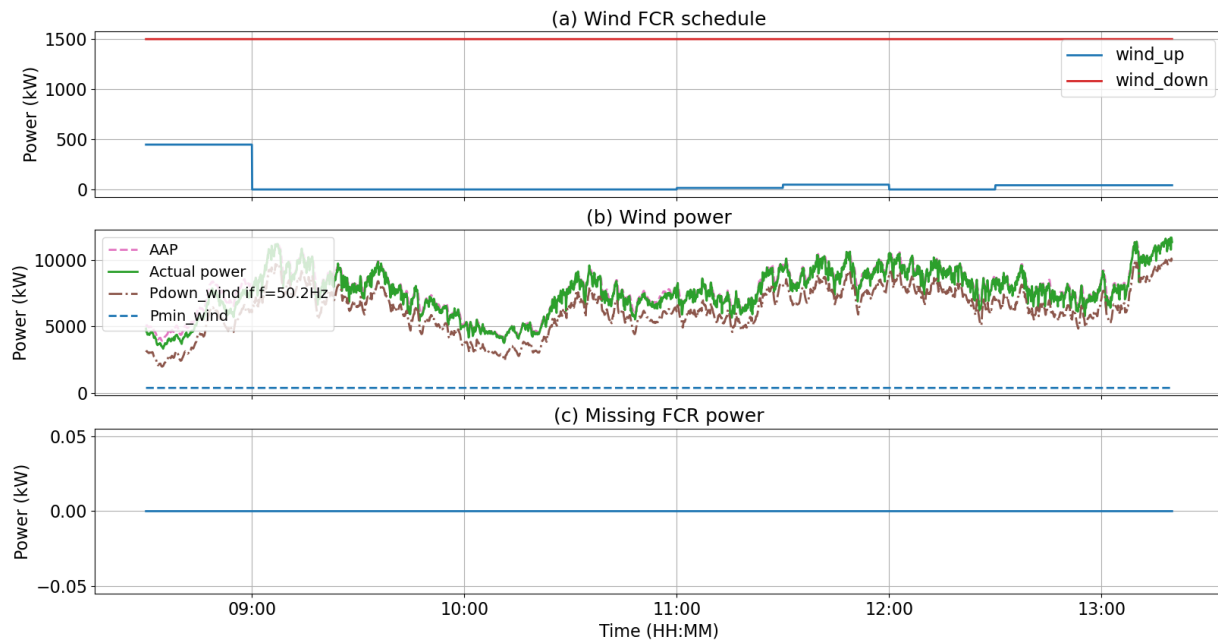
$$P_{missing_wind} = P_{min_wind} - (P_{AAP_est} - P_{FCR_up_wind} - P_{FCR_down_wind}) \quad \text{EQ. 14}$$

Figure 63 shows the analysis results of the wind / VPP reserve availability for the test performed on Oct. 22. During this test, despite the relatively low wind generation, the OPS had decided to provide some FCR based on wind reserve according to the day-ahead forecasts (Figure 63(a)). However, on the very day there was regrettably less wind than expected, which made the wind reserve not fully available over the entire FCR regulation band (Figure 63(b)), especially in the afternoon (Figure 63(c)).



**FIGURE 63. ANALYSIS OF THE LACK OF POWER FOR FCR RESPONSE IN CASE THE FREQUENCY REACHES 50.2 HZ
(TEST PERFORMED ON OCT. 22)**

One can therefore understand that the availability of the FCR is quite dependent on the quality of the forecasts as well as on the wind generation level. Similar analysis was performed for the test of Oct. 20. As illustrated in Figure 64, on this test day, the wind power was high enough to cover the forecast errors and to ensure both the upward and downward reserve delivery (the allowed minimum operating point would never be reached), leading to 100% of reserve availability (the lack of full capacity reserve was equal to zero during the whole period of the test).



**FIGURE 64. ANALYSIS OF THE LACK OF POWER FOR FCR RESPONSE IN CASE THE FREQUENCY REACHES 50.2 HZ
(TEST PERFORMED ON OCT. 20)**

Table 13 lists the assessed FCR availability for each full-chain experiment performed. It was found that on average, the FCR procured from the VPP was fully available during 64% of the total test time. Note that this availability can be further improved, as the wind minimum operating point was not modelled in the OPS for real tests. This parameter should have been considered in the scheduling phase, which would help increase the overall availability to at least 74% by post-processing the experimental data.

Test n°	Date	Duration	ARP
1	Oct. 20, 2021	5h	100%
2	Oct. 21, 2021	1h45	100%
3	Oct. 22, 2021	8h	34%
4	Oct. 28, 2021	7h	17%
5	Oct. 29, 2021	2h15	100%
6	Dec. 9, 2021	4h30	100%
7	Dec. 9, 2021	2h30	99.6%
Assessed ARP for the total duration of the tests			64%

TABLE 13. ASSESSED PERCENTAGE OF TIME OF "FULL AVAILABLE FCR"

As previously mentioned, one possible way to avoid the lack of FCR due to forecast errors is to take an additional power margin while scheduling (which will also result in additional costs). Another solution consists in reallocating a part of the committed wind reserve on the BESS, within the limits of available stocks, by activating the corresponding function of the STC control layer.

It is also important to notice that the obtained results were based on the participation of the VPP in the daily auction of the FCR market, which is the current situation, meaning that the FCR volume should be committed one day ahead of time. Apparently, this could still seem challenging, when reserve should be provided by RES, to fully ensure the availability of the committed reserve. **The reduction in procurement lead-time would be essential to enhance the wind reserve reliability** and to increase the declarable reserve by taking advantage of lower forecast errors. **A closer-to-real-time market will greatly promote the participation of new players such as wind generation or VPP in the FCR service, and will also allow for a more available and more efficient frequency service provided.**

4.2.2.3 RELIABILITY OF THE COMMUNICATION SYSTEM

The last KPI of the demonstration is dedicated to measuring the reliability of the applied communication and IT platform, which is one of the most important subsystems of the VPP, especially for the control and the monitoring of the remote distributed assets. As defined in Table 14, this KPI has been assessed by calculating the percentage of time during which all the necessary data exchanges for VPP operation were correctly ensured by the platform for all tests performed.

KPI n°6			
KPI name	Reliability of the communication platform	KPI ID	AVC
Main objective	Evaluate the performance of the communication and IT platform based on <i>GeneSys</i> solution applied in the French demonstration.		
KPI Description	To ensure the interoperability and scalability of the WP8 demonstration, a new full-IEC-61850-based and hardware-agnostic software and communication platform was developed and implemented by EDF R&D. The availability of the whole ICT (Information and Communication Technology) infrastructure and interface is essential to ensure the robust data exchanges between the centralised control and all the assets, so as to guarantee a proper functioning of the VPP and its full services delivery capacity. This availability can be measured in percentage of the time during which the communication infrastructure is working as expected.		
Unit	%		
Formula	$AVC[\%] = \frac{T_{com}}{T_{op}} \times 100\%$ <p>Where:</p> <p>T_{com} [s] is the total duration in which all the communication platform is working correctly as defined in the demonstration specifications.</p> <p>T_{op} [s] is the total running time of the VPP during the experimental tests.</p>		
Target value	as close to 100% as possible		

TABLE 14. KPI N°6: RELIABILITY OF THE COMMUNICATION AND IT PLATFORM

It was observed that over the 7 full-chain tests (31 hours in total), the data exchange problem occurred once on December 9 and lasted 6 minutes. As shown in Figure 65, the feedback signals from the wind farm transmitted by GED-W device were "frozen" at around 11:30 on the day of the test. In the meanwhile, other GED devices responsible for the communication with the assets installed at Concept Grid seemed to work well.

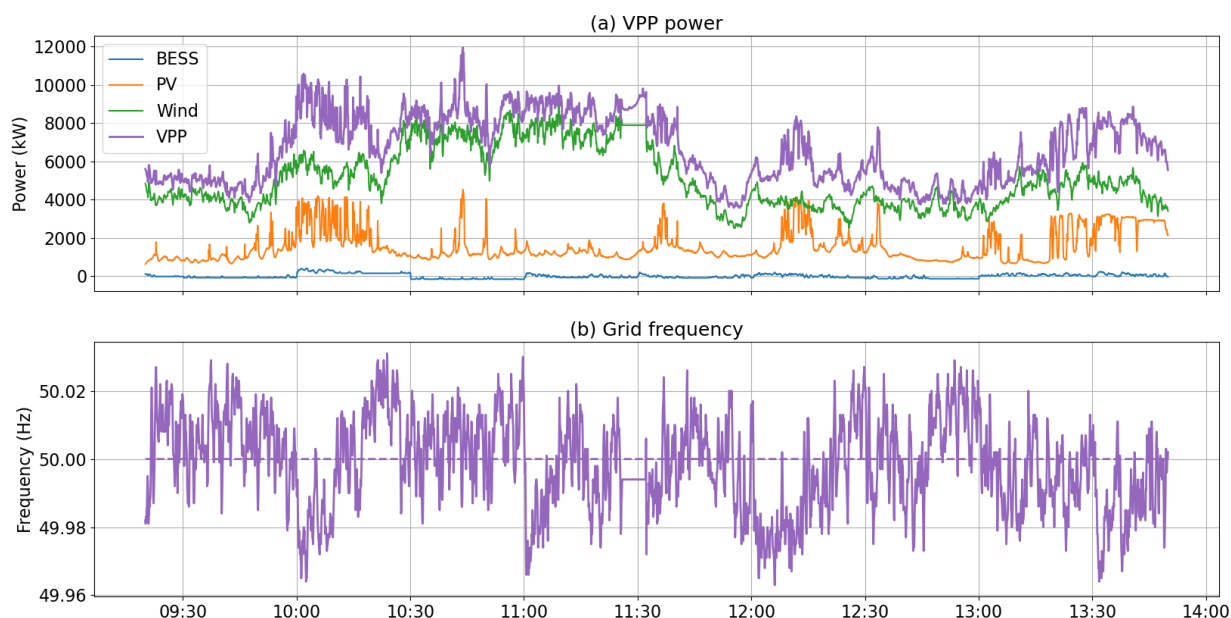


FIGURE 65. OCCURRENCE OF THE COMMUNICATION PROBLEM ON DEC. 9, 2021

In addition, a windstorm in the region where *Anglure* farm is located was also experienced on Oct. 21 (started since the night of Oct. 20), which completely stopped the wind generation as well as the Internet connection of the wind site. The whole communication platform was then re-established on the very day following manual interventions. Due to this reason, the duration of the test on Oct. 21 was shorter than the other days. Nevertheless, this problem observed was rather related to an extreme weather condition than to the reliability of the communication platform.

The calculated overall AVC equals to 99.7%, meaning that **the implemented VPP communication platform, based on GeneSys solution developed by EDF R&D, is highly reliable most of the time during normal operation.** As a reminder, from the perspective of replicability and scalability of the demonstration, *GeneSys* solution also allows a simple and standardized integration of new components in the management portfolio of the VPP. However, note that there were still some software instabilities which required sometimes to restart *GeneSys* before a test to ensure its proper functioning during the test. This can be further improved in the next versions of the solution for industrial applications.

According to the experience of the French demonstration, the communication infrastructure of a VPP is of great importance and could be challenged by the wide geographical distribution of the assets. It needs to be robust enough to ensure dynamic and stable exchanges of a large amount of data within the VPP and with external interfaces, but also reliable and cyber-secured. Supervision and monitoring of the telecom assets must be

implemented to guarantee availability and cybersecurity. It is also recommended that ICT-related components and operational control modules / hardware should be physically separated to avoid possible interference. Similarly, functional data flows for the VPP operation should be logically separated from data flows for the communication supervision /monitoring /management, by means of VLAN, to make sure there is no interference and to apply Quality of Service (QoS).

5. KEY FINDINGS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The aim of the WP8 demonstration was to develop, set up and test a virtual power plant (VPP) endowed with multiple-service provision capabilities in the perspective of a power system with a high share of variable renewable generation.

The VPP includes a portfolio of decentralized assets: a 12-MW wind power plant, a photovoltaic (PV) generation unit and a 2-MW/3-MWh battery energy storage system (BESS). Thanks to the central energy management system (EMS), the different assets were managed in a coordinated and optimal manner. Based on multiple criteria such as weather forecasts, energy and services market prices and availabilities of assets, the developed EMS was capable of providing optimal energy and multi-service schedules for the VPP and allocating frequency reserve on the controlled assets, at regular intervals, by considering the most recent forecasts and measures.

To allow intensive offline tests in a cost-effective way and to de-risk the demonstration, an advanced offline simulation platform was developed based on software modules and dynamic models of local assets. Some economic key performance indicators (KPIs) were also assessed using this platform, by precisely simulating the behaviour of the whole VPP system, in real or almost real conditions, over weeks. The following points were highlighted through offline simulations:

- **The provision of frequency containment reserve (FCR) in addition to energy arbitrage helps increasing the VPP revenue, but also enables the VPP to effectively contribute to the resilience of the power system.**
- **It is beneficial to have a joint participation of the wind farm and the storage in FCR provision**, as it not only gives the BESS more flexibilities for energy arbitrage, but also highly increases the economic opportunities for the participation of wind generation by allowing a symmetric reserve provision while avoiding unnecessary and costly renewable generation losses.
- Forecast errors could significantly reduce the full income of the VPP due to the costs for power imbalances settlement. **A VPP program scheduling based on stochastic optimization, by considering probabilistic generation forecasts, can efficiently reduce power imbalances** with respect to the commitments, which could result in higher overall revenues.

For the purpose of online testing, a full IEC-61850-based and hardware-agnostic communication platform was applied in this demonstration. The platform presents several advantages such as the flexibility to manage the software, firmware and configurations on remote devices and the increased level of cybersecurity. Its reliability has been proven during the tests. Its ability to enable a simple and standardized integration of new assets into the VPP management fosters the scalability and the replicability of the demonstrated solutions.

Local tests were first performed on site for each asset to validate the good operation of the control algorithms for services provision. Even if flexibility solutions such as ramp rate control (RRC) were successfully demonstrated, the focus was on frequency services. Not only the "common" form of reserves, such as frequency containment reserve (FCR) and frequency restoration reserve (FRR), but also the emerging new form of frequency regulation, such as fast frequency response (FFR), were tested and assessed. **Globally, the performance of the frequency services provided by the wind farm and the BESS complied with the requirements imposed by the TSO. Their fast responsiveness led to very high performance in terms of dynamics.** In addition, the capability to provide simultaneously multiple services was also evaluated.

The complete operation of the VPP was demonstrated through full-chain tests over 30 hours, during which all involved subsystems worked seamlessly, and all the assets were autonomously managed by the EMS. It was observed that **most of the time the operational planning scheduler allocated only downward reserve to the wind farm**, as shortfalls related to wind generation curtailment for providing upward reserve were properly modelled and considered. Upward reserve was scheduled to be provided by the wind farm only for economic reasons (e.g.: the BESS capacity should be kept for an optimal use in the next hours or the FCR market price was sufficiently high to cover the costs of curtailment) or in case of technical constraints (e.g.: the battery was not available due to a low state of charge).

Even though the performance of the VPP was shown to be satisfactory, the demonstration highlighted two important key points that deserved particular attention:

- **The availability of the reserve provided by the VPP is greatly dependent on the accuracy of the wind forecasts.** It was showcased that in the context of the current market design which requires the FCR to be contracted a day ahead of time, the inevitable forecast errors could lead sometimes to the partial or even complete unavailability of the committed reserve on the very day. This means that additional power margin should be considered for wind reserve constitution while performing day-ahead scheduling, which will however entail negative economic impacts.
- **The accuracy of the estimation of wind instantaneous available active power (AAP) is another key factor to ensure the performance of the frequency reserve provided**, notably in terms of FCR control gain assessment. The AAP estimator applied for the EU-SysFlex demonstration would need to be further improved. In some circumstances (e.g.: severe wind gusts), the AAP was overestimated, leading to insufficient reserve delivery with respect to the grid frequency, and thus, to a drop in frequency control performance.

In conclusion, the work in WP8 demonstrated the capability of the wind power plant and the BESS to provide multiple flexibility services to the grid but as well their limitations. The VPP was able to aggregate and to better use individual capabilities, while mitigating, to a certain extent, individual shortcomings. An optimal and coordinated management of several decentralised resources could enhance the performance of the services provided and create more opportunities for the participation in services markets.

5.2 LESSONS LEARNT AND RECOMMENDATIONS

5.2.1 WIND FREQUENCY CONTROL

One of the important innovations of the WP8 demonstration consisted in testing and assessing the active power reserves provided by wind generation. It was demonstrated that wind technology can efficiently contribute to frequency regulations (FFR, FCR and FRR), based on active power modulation, when a minimum level of generation is available (typically from about 15% of the rated power).

The notion of the estimated “available active power” is of great importance, as it is the baseline power for the procurement of the expected amount of reserve and for the calculation of frequency control setpoints. A standardized definition of the wind AAP has to be given by normative bodies in agreement with system operators (SOs), regulators, producers and manufacturers. The available active power estimator applied in the EU-SysFlex demonstration worked properly but also showed some limitations in case of extreme variations of wind. The estimation method can be further improved by manufacturers to have a better accuracy; however, they may need clearer incentives from the markets to proceed.

Another aspect concerns the qualification and performance check processes to verify the quality of the frequency response provided. The method used in our demonstration was the same as that currently applied by the French TSO and designed for assessing the reserve procured from conventional power plants. It needs to be revised by SOs in the future while considering the specificities of renewable generation (e.g.: when frequency reserve is provided by a generator based on variable baseline power instead of constant baseline power).

From an economic point of view, reserve procurement from wind generation seems still questionable due to the current FCR market design. It was demonstrated that day-ahead reserve commitment currently required turned out to be challenging for a wind farm to guarantee its reserve availability in real time, due to inevitable forecast errors. Although some of the FCR market characteristics such as product length, resolution and gate closure time have recently been reduced in Europe, which is already a first step to arouse the interest of renewables, a closer-to-real-time market seems better to fit with forecasting limits and to enhance the wind reserve reliability. However, this adaptation in market rules requires a full cost-benefice analysis, which has not been carried out in this deliverable, to assess all the impacts of this change on the overall supply costs of the FCR at the power system perimeter. Furthermore, in terms of the product form, asymmetric reserve should be allowed to promote the participation of new players such as wind generators, as they are more suitable for providing downward reserve only. Upward reserve provision is possible but leads to undesirable shortfalls, which need to be compensated by participating in FCR.

5.2.2 VPP OPERATION

Virtual power plants aggregating renewable generation and storage have a good technical potential for providing flexibilities and ancillary services. The inclusion of a storage system into the VPP management further enhances the quality of the services provided, by compensating renewable generation variabilities and by increasing the

dynamics. Coordinating diverse assets owning each one its proper technical specificities would increase the availability of the services, especially at a large level of several renewable power plants, compared to that procured from single units. Besides frequency controls, voltage supports are also possible at a local level (which were not tested in the WP8 demonstration but were technically available) and other flexibilities can also be provided when the power system needs appear, such as generation smoothing and ramp-rate control. Hence, SOs should carefully consider the exploitation of the technical potential of virtual power plants in fulfilling the flexibility needs of future power systems.

To monitor and control several distributed assets, which could be geographically widespread, a robust and secured communication architecture is essential for the VPP operation, while bearing in mind that the scalability and potential improvements of the solution are also of great importance. In terms of architecture, the communication system should enable an easy integration of new components and allow efficient and remote updates of local control algorithms, in order to be better adapted to fast-moving grid-side requirements and evolving market conditions.

The communication medium chosen should be as reliable as possible. It is recommended to use optic fibre or copper wire access whenever possible and 4G/LTE as a last resort. In any event, network access is a primary issue when considering the VPP's communication and the choice of the solution must be made according to the technical knowledge of the network operator and in agreement with him.

VPN and Internet Protocol Security (IPsec tunnel) infrastructure need to be implemented to secure and encrypt data exchanges between operational sites. Furthermore, supervision and monitoring of the telecom assets must be implemented to guarantee availability and cybersecurity. It is recommended that ICT-related components and operational control modules / hardware should be physically separated to avoid possible interference. Similarly, functional data flows for VPP operation should be logically separated from communication data flows, by means of VLAN, to make sure that there is no interference and to apply quality of service.

From an economic point of view, virtual power plants should also be more seriously envisaged, as this could be a solution to allow the participation of renewable generation in existing frequency reserve markets while preventing shortfalls of individual assets. For example, downward reserve could be provided by wind or PV assets whereas storage assets can provide upward reserve (seen from the asset level, the frequency response can be upward or downward only, but seen from the VPP level, the product is symmetric and fits with the existing market requirement). Moreover, renewable generation could be used to charge the storage when necessary, to avoid useless curtailment or energy purchase from the grid, when they are located at the same site. Shortfalls are then prevented at the asset level, and conversely revenues are increased at the VPP level. Additionally, a VPP management could help small producers enter the markets more easily by aggregating a certain amount of generation, storage and consumption. This would also "simplify" SOs' tasks of managing different services providers, by keeping their amount at a reasonable level from a SO point of view.

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