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# Report detailing the flexibility market framework and specific product design details

Deliverable 4.1

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Deliverable D4.1
REPORT DETAILING THE FLEXIBILITY MARKET FRAMEWORK AND PRODUCT DESIGN DETAILS

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# DELIVERABLE 4.1 – VERSION 0.4
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| **DEC** | Demonstrator, pilot, prototype, plan designs | |
| **DEM** | Websites, patents filing, press & media actions, videos, etc. | |
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| **PU** | Public | X |
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More information on the project can be found at https://www.maesha.eu

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# EXECUTIVE SUMMARY

## Context

The energy landscape of European geographical islands significantly differs from the continental area and faces many challenges of costly, unreliable, and environmentally polluting energy supply. In this context, MAESHA project focuses on fostering the penetration of renewable energy sources and enabling the deployment of flexibility and energy management solutions on geographical islands to overcome these challenges. However, to enable the procurement of these flexibility services, tailored market solutions are required. This task is challenging because the diversity of islands in terms of natural environment, size of their power systems, different regulatory conditions, social welfare level, etc. complicate the design of replicable flexibility products and a market design that is tailored towards the context of geographical islands.

## Purpose of this report

The report describes a path from technical scarcities that are vital for geographical islands to system services that mitigate these scarcities and to options for flexibility market design, including potential flexibility market innovation. The flexibility market design is treated as a composition of product and auction design. In particular, the auction design specifies the definition of trading principles, including interaction schemes, and methodologies for market procurement and settlement. The product design defines technical dimensions of flexibility products such as form of response, time attributes of the response, and activation conditions. The objective of the flexibility market design is to maximize social welfare considering such criteria as operational security, cost-efficiency, environmental benefits, regulatory and operational compatibility with local operation management, market liquidity, real-life implementation constraints and complexity.

## Scope and limitations

The report investigates the flexibility product and market design for the use cases of “Frequency control”, “Minimization of the consumption peak”, and “Voltage control” presented in MAESHA deliverable D1.1 “Use-cases Requirements and KPIs definition”. The use cases are developed for power system of Mayotte island located in the French overseas region where MAESHA solutions will be piloted.

The supporting goal of this report is to provide the design requirements for the development of flexibility management and trading platform in MAESHA project. Therefore, the focus of the design is on the use cases of frequency control and minimization of the consumption peak, as these are to be implemented in the flexibility management and trading platform, whereas the voltage control is based on a bilateral interaction between the system operator and the flexibility service providers and hence some of the design attributes are omitted from the report and will be defined in the corresponding agreements.

Furthermore, the development of the liberalized energy market design for the geographical islands, including implicit flexibility management by tariffs, is out of scope of the current report, and this report solely investigates explicit flexibility products and flexibility markets.

## Methodology

The design of the flexibility market is based on a newly developed flexibility market framework. The framework provides a uniform structure for the description of product and auction attributes. The framework is applied to three design scenarios: *EDM-BAU* design scenario describes business-as-usual practices of electric utility on Mayotte island, *FMTP-DEMO* scenario shows the planned design scheme that will be applied during the project pilot demonstrations, and *FMTP-FUTURE* scenario provides the recommended design attributes for the auction design that should also serve as a reference to follower islands of MAESHA project. These auction design attributes for individual scenarios are examined toward the selected design criteria.

## *Main contributions*

The main contribution of this report is the description of the design scenarios for the flexibility market tailored to the geographical islands. The evaluation of the presented design scenarios provides a reference mainly to the electric utility on Mayotte island, but also to the follower islands for the adoption of a flexibility market in short-term operational planning.

Finally, this report provides a comparison of product differentiation methods and evaluates their compatibility within the context of geographical islands. The study concludes that the conditions of a high diversity of islands in terms of their population and size, level of renewable energy sources penetration, technical scarcities make challenging a development of a harmonized flexibility market design. In many of these cases, special product differentiation would be required to fulfil the technical scarcities. However, the ultimate product differentiation causes further fragmentation of the underlaying markets and creates conditions for market participants to exercise their market power. Therefore, the study considers that the blueprint model for island flexibility market should consider market restructuring. This process enables a ‘supermarket’ approach for the flexibility product specification and allows all technologies to participate in the market and enables the system operators to optimize the procurement of the resources based on their capabilities.

## *Report outline*

The report consists of the following chapters:

**Chapter 1:** introduces the MAESHA project, describes the scope of work package WP4 and task T4.1 within the project, and summarises previously conducted European H2020 research projects related to the task objectives.

**Chapter 2:** describes the technical background of the report including definition of system services and its difference from the product definition, roles of market actors used in the market design, market liquidity challenges in the island context, and operation of Mayotte power system that will be used for pilot demonstration of the MAESHA solutions.

**Chapter 3:** presents the methodology of the flexibility market design, including considered design scenarios, components of the desktop analysis, design criteria, use-case specific qualitative and quantitative assessment analyses, and feedback process interactions.

**Chapter 4:** specifies the system services considered for the flexibility market design and defined in task T1.1 of MAESHA project for use cases of “Frequency control”, “Voltage control”, and “Minimization of the peak consumption”. The description of system service concise the technical scarcity it solves, theoretical description of the service and product classification, overview of the state-of-the-art products, potential service providers, current practices of electric utility on Mayotte island to address the scarcity, and objective of the use cases in MAESHA project.

**Chapter 5:** introduces the theoretical market design framework used to design the flexibility market in MAESHA project. The framework provides a detailed description of its components divided into *product specification* and *auction specification* each consisting of a set of stages with design attribute options.

**Chapter 6:** specifies the proposed product and auction design for the predefined use cases according to the flexibility market design framework. The specification of the products is defined for demonstration activities of MAESHA project. The specification of auction design primarily covers the demonstration needs but also describes and evaluates some stages of the theoretical market framework for the design scenarios of current practices of electric utility on Mayotte island, the project pilot demonstrations, and future recommendations.

**Chapter 7:** explains the innovation potential that can be applied to the organization of flexibility markets on geographical islands. The chapter starts with introduction of methods to product specifications and their compatibility with the context of geographical islands. Then, an example of market restructuring to achieve the suggested product specification is shown.

**Chapter 8:** concludes the report with summary of the outcomes of present study. The conclusions are focused on summarizing the reasons for the selection of auction specifications in particular design scenarios in respect to selected design criteria. Furthermore, this chapter outlines the innovation potential for the organization of the flexibility markets on geographical islands.

# LIST OF FIGURES

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# NOTATIONS, ABBREVIATIONS AND ACRONYMS

Table 1: Acronyms used in the document

| | |
|---|---|
| ABO | Asymmetric Block Offer |
| aFRR | Automatic Frequency Reserve Restoration |
| AGC | Automatic Generation Control |
| AOF | Activation Optimisation Function |
| BESS | Battery Energy Storage System |
| BSP | Balancing Service Provider |
| CCTU | Capacity Contracting Time Unit |
| CPG | Capacity Providing Group |
| CPU | Capacity Providing Unit |
| CRE | French Energy Regulatory Commission |
| CSP | Capacity Service Provider |
| DER | Distributed Energy Resource |
| DR | Demand Response |
| DSO | Distribution System Operator |
| EBGL | Guideline on electricity balancing |
| EDM | Electricité de Mayotte |
| EV | Electric vehicle |
| FCR | Frequency Containment Reserve |
| FFR | Fast Frequency Reserve |
| FiT | Feed-in tariff |
| FMTP | Flexibility Management and Trading Platform |
| FRCE | Frequency Restoration Control Error |
| FSP | Flexibility Service Provider |
| KPI | Key Performance Indicator |
| LER | Limited Energy Reservoir |
| MBMA | Meter before – meter after |
| MFR | Minimum Flexibility Requirement |
| mFRR | Manual Frequency Reserve Restoration |
| MIQP | Mixed Integer Quadratic Program |
| MRR | Minimum Reserve Requirement |
| MRTS | Marginal rate of technical substitution |
| PAL | Peak-above-limit |
| PPA | Power Purchase Agreement |
| PV | Photovoltaic |
| RES | Renewable Energy Source |
| RoCoF | Rate of Change of Frequency |
| SOGL | Guideline on electricity transmission system operation |
| SO | System Operator |
| TSO | Transmission System Operator |
| UUID | Universal Unique Identifier |
| VPG | Voltage Providing Group |
| VP | Validity Period |
| VPP | Virtual Power Plant |
| VPU | Voltage Providing Unit |
| VSP | Voltage Service Provider |

# 1 INTRODUCTION

This chapter introduces MAESHA project, describes the scope of work package WP4 and task T4.1 within the project, and summarises previously conducted European H2020 research projects related to the task objectives.

## 1.1 MAESHA PROJECT

The European Union includes over 2400 islands that are populated by more than 16 million people. Despite having diverse nature environments, these islands face similar challenges of energy supply such as high dependency on imported fossil fuels (mainly oil) and their limited supply, weak level or a lack of electricity and gas interconnections, high energy costs, low security of supply with often interruptions, lack of economies of scale, and energy poverty. However, the natural island conditions have high production potential for solar, wind or biomass technologies that can be leveraged to overcome some of energy supply challenges. A large share of renewable energy sources (RES) combined with tailored flexibility services could ensure a higher energy independence, provide more reliable security of supply, and guarantee grid stability while reducing the costs of energy for customers.

In this context, the main objective of MAESHA project is to enable the deployment of flexibility and energy management solutions to foster the penetration of RES on geographical islands, and thus decarbonize the energy sector. This objective is achieved with multi-axis approach relying on tailored flexibility market and business framework design, exploration of energy-sector synergies, multi-horizon modelling of island energy-economy and power system operation, development of flexibility management and trading platform and energy management systems for aggregation, and involvement of the end-uses in the energy management via local community structures. MAESHA will demonstrate the solutions on the French overseas island of Mayotte and study the replicability potential on 5 follower islands representing more than 1.2 million inhabitants spread in geographical Europe and overseas territories.

## 1.2 WP4 OBJECTIVES

Work package WP4 focuses the development of innovative and tailored flexibility market design and business models based on deep analysis of the particularities of the insular energy markets in coherence with the technological solutions proposed in MAESHA. This work package investigates the commercial viability of the project and determines the business models and cost implications of the developed solutions by specifying an underlying market design and business models for different market players, aligning the solutions with the local regulatory framework, and providing policy and regulatory recommendations for an efficient flexibility market uptake on islands.

## 1.3 TASK OBJECTIVES

Task T4.1 aims to explore the flexibility market and product design tailored to geographical islands. This task consists of *Subtask 4.1.1 Energy market framework* and *Subtask 4.1.2 Detailed product design*. The flexibility market design focuses on the definition of trading principles, including interaction schemes, market timeframes, remuneration principles, and methodologies for market procurement and settlement. The flexibility product design defines technical dimensions of flexibility products such as form of response, time attributes of the response, and activation conditions.

Currently, no comprehensive flexibility market design and flexibility products specifically tailored to geographical islands exists today. A tailored flexibility market design shall address the challenges of system reliability and cost-efficiency that islands face. The technical challenges include low system inertia, high variability of RES production (especially solar and wind), and a limited or non-existing grid interconnection to the mainland. Moreover, the market challenges include low market liquidity, lack of standardized flexibility products, and a vertically integrated energy market structure that shall be aligned with a potential flexibility market. To derive flexibility from the demand side and RES or to attract private investors in renewable energy, a proper flexibility market design should allow European islands to create conditions wherein these stakeholders can create business models with sufficient revenue predictability, while simultaneously minimizing the energy prices and balancing costs.

Another crucial barrier for the development of a scalable flexibility market design is a high diversity of islands in terms of their population, level of RES penetration, and geographical size. As a result, a crucial point of attention is the replicability potential that should be considered to make sure that European islands different in terms of system size and parameters, the available technical and human resources, and the requirements for the system services can easily adopt the proposed solutions. Ideally, the proposed solution shall be modular, having a base requirement suitable for the smallest island and proposing more advanced features to improve the market functioning and product efficiency. In terms of complexity, the planning horizon of the design shall be in line with the fast-developing information technologies and automation control solutions. A look into the future shall consider increasing RES capacity, newly introduced distributed energy resources (DERs), and roll-out of smart meter infrastructure.

Considering the diversity of potential solutions for energy dispatch on islands, the market shall operate in parallel with the existing energy dispatch methods. The platforms supporting current functionalities of system operators can be too rigid and slowly evolving to support an integration with an emerging technology and business. The independence of operation, however, should not disturb the establish operational practices but complement them.

Therefore, due to the specific challenges of islands, it is indispensable to produce an innovative, replicable market design that can mitigate unique technical and market conditions of geographical islands. At the same time, the isolated structure of the islands provides an ideal ground to explore innovative solutions that later could be applied in the continental Europe in the context of microgrid solutions.

## 1.4 SCOPE OF THE DOCUMENT

Task T4.1 is centrally positioned within the project structure affecting its overall development. The complete diagram of interactions of T4.1 with other WPs is illustrated in Figure 1.

### 1.4.1 Inputs for task T4.1

The initial work for the progress of task T4.1 has been done in task T1.1 on the definition of generic use cases of “Frequency control”, “Voltage control”, and “Minimization of the peak consumption” that will be piloted on Mayotte island. The use cases described in deliverable D1.1 provide the actors list, scenarios, and information flows, as well as some requirements for the demonstration of the use cases that serve the basis for their further product and market design in task T4.1.

Moreover, the task T4.1 relies on the results of technical energy system modelling from work package WP2. In particular, the results of power system dynamics model from T2.5 provide information how technical dimensions of the product design affect stability of the island power system. Furthermore, T2.3 provided assumptions for the future development of the energy-economic system of the Mayotte island up to 2030 and 2050 that allowed us to assess the need and suitability of the proposed flexibility products and the potential technologies that can be installed on the island. Additional input contributions are the recommendations regarding the market structure received from T4.2, which are based on the analysis of the regulatory framework for Mayotte island, and which provide an overview of the energy investment opportunities.

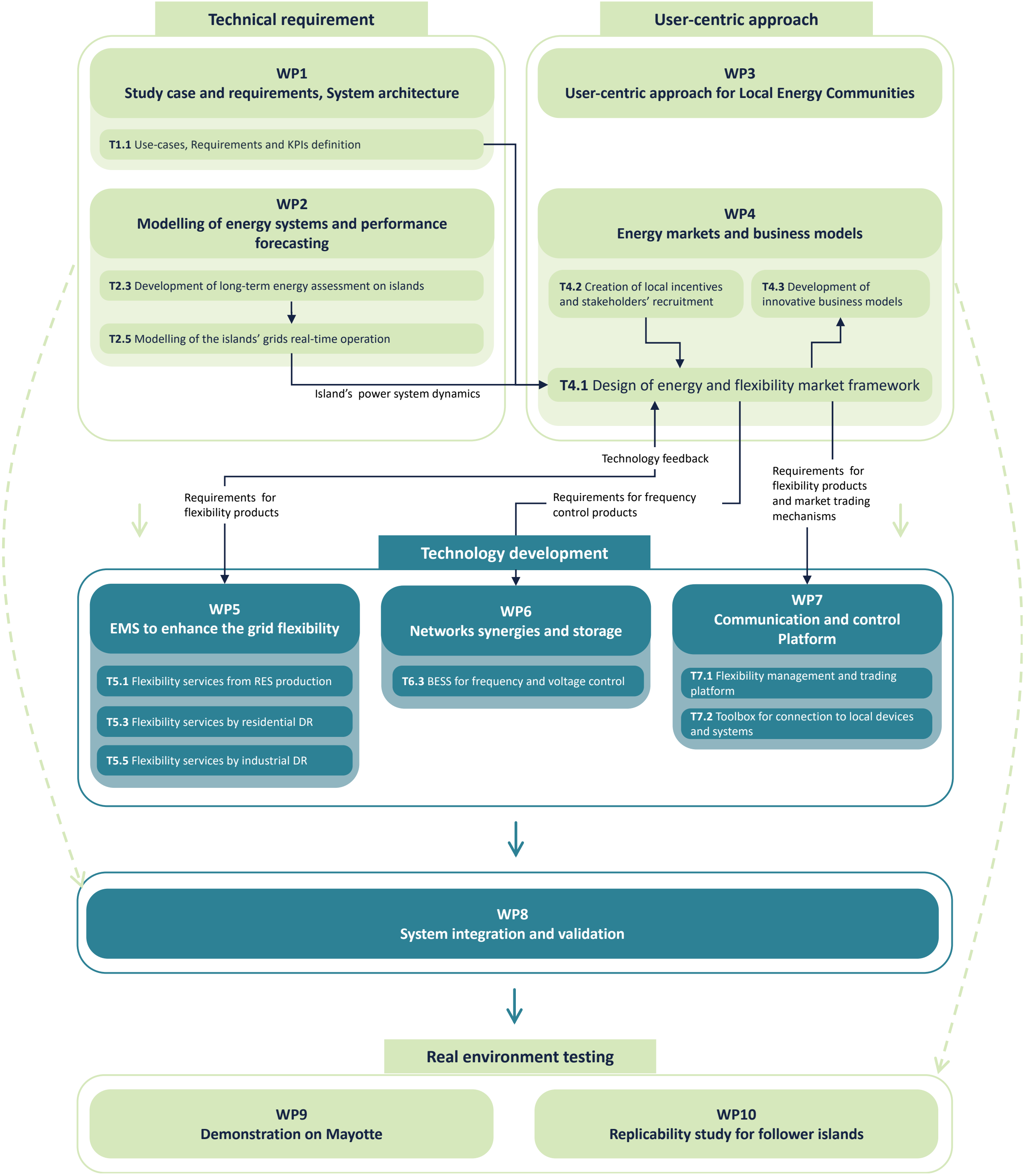

Figure 1: Scope of task T4.1 in MAESHA project

### 1.4.2 Outputs from task T4.1

The results of the T4.1 are leveraged within WP4, WP5, WP6, and WP7. The definition of the flexibility products and markets are used in T4.3 for the development of novel business models. Furthermore, the partners in WP5 (tasks T5.1, T.5.3, and T5.5) use the results of flexibility product design to develop flexibility services for demand response (DR) of residential and industrial customers as well as yield flexibility from renewable sources. These partners will also provide technology feedback regarding the compatibility and limitations of the design to available demand and supply (including RES) technologies. In task T6.3, Inputs from task T4.1, regarding the product design will be used to define the specifications of the battery storage energy system (BESS) for frequency and voltage control that will be further demonstrated in the project pilot. Finally, the specifications of flexibility product parameters and market trading rules serve as an input to the design of the flexibility management and trading platform toolbox in task T7.1 and communication toolbox task T7.2, which are both essential for the project demonstrations.

## 1.5 RELEVANCE TO EU PROJECTS

The studies in this work package are related to activities in the several European projects. However, in all the related projects, the underlaying context is focused on the flexibility market and product specification for continental Europe. Nevertheless, some of the findings and methodological approaches are applicable to the current task. In what follows, these projects are shortly introduced, and relevant works are states.

CoordiNet project[1] aims to define and test a set of standardised flexibility products and the related key parameters for system services, including the reservation and activation process for the use of the assets and finally the settlement process. In this project, deliverable D1.3 elaborates on the harmonized products for the exchange of system service by distribution system operator (DSO) and transmission system operator (TSO), and deliverable D2.1 provides the definition of markets for DSO and TSO procurement of innovative system services.

EU-SysFlex project[2] focuses on the market solutions associated with integrating large-scale renewable energy on the pan-European power system: from the development of novel approaches for system operation with high renewables, to market design and regulatory requirements, as well as integration of new system services and data management plans to cover the pan-European market. Work package WP3 concerns an analysis of market design and regulatory options for innovative system services. Deliverable D3.1 provides the product definition for the innovative system services, deliverable D3.2 describes the related market organization, and deliverable D3.4 investigate the impact of market and regulatory options using power system and market modelling.

OneNet project[3] focuses on large-scale demonstrations of innovative grid services through DR, energy storage, and small-scale RES generation. Work package WP3 of OneNet project aims to define a theoretical market framework for innovative market designs options (Task T3.1), study market integration aspects and interrelations of new market mechanisms with existing energy and flexibility markets (Task T3.2), analyse potential market distortions and inefficiencies of integrated markets (Task T3.3) and ensure alignment between developed concepts of market design, the regulatory framework, and the demonstrations within the project (Task T3.4).

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[1] https://coordinet-project.eu/

[2] https://eu-sysflex.com/

[3] https://onenet-project.eu/

# 2 TECHNICAL BACKGROUND

This chapter describes the technical background of the report including definition of system services and its difference from the product definition, roles of actors and entities used in the market design, market liquidity challenges in the island context, and operation of Mayotte power system that will be used for pilot demonstration of the MAESHA solutions.

## 2.1 DEFINITIONS

In this report we follow the definition of system service and product from (EU-SysFlex, 2018). *System service* or *flexibility service* is defined as the physical function (action), which is needed to mitigate a particular technical scarcity or scarcities and ensure secure and reliable operation of a transmission or distribution system in both short-term and long-term. A physical function is considered as a provision of active or reactive power and/or energy, while the technical scarcity is a deviation of the power system from a nominal operation state shown by a deviation from a nominal frequency or voltage levels. A *product* is a technical good that can be purchased and remunerated. For instance, peak DR is a product, while the system service is the provision of active power during peak demand period. Furthermore, we define an *auction* as a trading process wherein market participants place bids to purchase flexibility products.

## 2.2 OVERVIEW OF THE ROLES TO BE USED IN TASK

To describe different possibilities for organizing the procurement of flexibility products, a list of roles involved is necessary. From the regulatory point of view, the power sector of an island power system is typically organized using a *single buyer model*. In this model, electric utility manages generation, transmission, distribution, and supply of electricity with regulated pricing control and governmental supervision. The market competition is only introduced in the supply of electricity with some level of private sector participation via independent power producers such as solar photovoltaic (PV) owners selling electricity to the state utility through power purchase agreements (PPAs) or private suppliers (auto producers), which are connected to the distribution grid (Hadush, 2019).

The single buyer model used in this task is illustrated in Figure 2. Here, we consider that the operation of island power system is managed by vertically integrated electric utility. We refer to the System Operator (SO) as the part of the electric utility that oversees the system management. System operators are single buyers of flexibility creating a monopsony market environment. The role of SO is narrowed down to transmission system operator (TSO) or distribution system operator (DSO) given the context in which the system service is used.

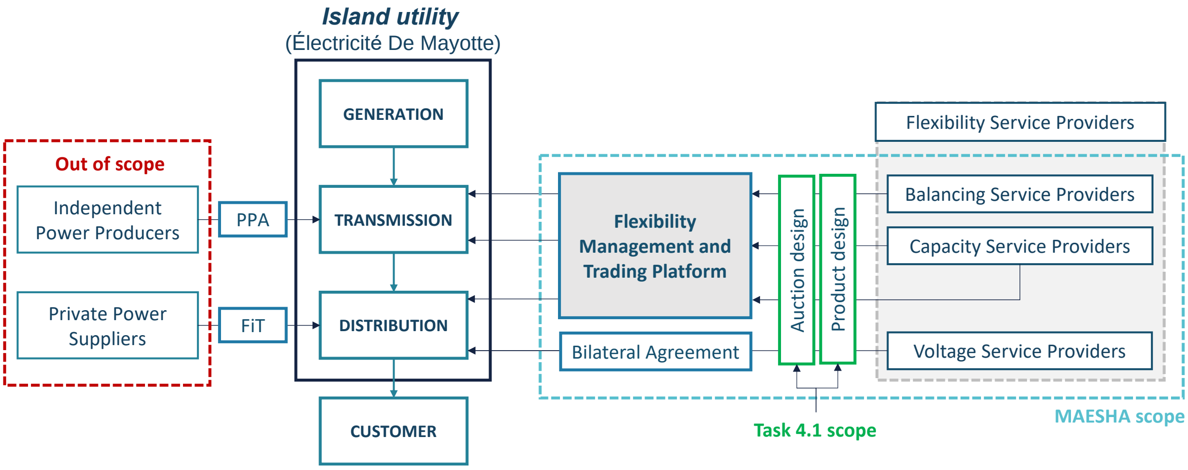

Figure 2: Market scope and roles used in task T4.1

Furthermore, we use notation of Flexibility Service Provider (FSP) as a reference to the entity that ensures the market interface between the flexible resources and flexibility market. Flexibility Service Provider acts as Balancing Service Provider (BSP), when the FSP role is used in the context of balancing services, Capacity Service Provider (CSP) if used for peak demand reduction, or to Voltage Service Provider (VSP), when voltage service is the objective.

The resource participating in the market is referred to Flexibility Providing Unit (FPU). The products are tailored for Generation, Consumption, and Limited Energy Reservoir (LER) FPUs. A group of FPUs with aggregated control, e.g., Virtual Power Plant (VPP), is referred to as Flexibility Providing Group (FPG). Both FPU and FPG can be referred to as Reserve Providing Unit (RPU) and Reserve Providing Group (RPG), when they are used in the context of balancing services. Similarly, the resources providing peak demand response are defined as Capacity Providing Units (CPUs) and Capacity Providing Groups (CPGs). Finally, resources providing voltage control are referred to as Voltage Providing Units (VPUs).

A role of Market Operator belongs to the entity that operates Flexibility Management and Trading Platform (FMTP). The role of Optimization Operator that carries optimization of a certain process, e.g., optimisation and/or selection of market bids, can be embedded into each of the entities listed above or be a separate entity.

## 2.3 MARKET LIQUIDITY CHALLENGES

The European directive on the internal electricity market (EU) 2019/943 requires adopting a market-based approach for procurement of system services in favor of contractual processes if it is economically efficient to do so. The main challenge of organizing a market-based procurement in island power system with limited capacity offers and number of participants is a high possibility of oligopolistic outcomes that can range from competitive, effective oligopolistic competition in which no super-normal profit is made, to non-competitive market outcomes that violate social welfare (BEREC, 2015). The reason for the non-competitive market outcomes is an ability to profitably alter prices away from competitive levels by market participants exercising their market power (Stoft, 2002). Here, market power is referred to as an ability of market participants to behave strategically and manipulate product prices to increase their profits. Typically, the market power arises in the conditions when the market participant owns large share of the market or provides exclusive product as in a monopoly. If there are several flexibility service providers holding market power and exercising strategic bidding collectively or individually, then such market condition is referred to as an oligopoly. As geographically isolated islands have limited amount and diversity of potential flexibility service providers, there is a low probability to achieve completive pricing outcomes under market-based solution.

The criteria for perfect competition include atomic market structure, no entry or exit barriers, perfect information, and homogeneity of the product. In practice, however, all the criteria of perfect competition cannot be held even for frequency control services in continental Europe (ELIA, 2020). The problem of market liquidity for islands can be compared with the problem of liquidity that arises for local energy markets or voltage control that have local nature and hence have a limited amount of flexibility service providers that can mitigate the issue. Considering the risks of market power abuse, such services are typically renumerated with a regulated price in contrast to a market-based[4] solution.

To prevent market exercise, the preliminary assessment of the market power can be done at the prequalification stage when the prequalified volume of flexibility becomes known. Furthermore, the gaming on the market can be reduced via competition laws/regulatory oversight, so that prices are determined by competition rather than being arbitrarily regulated. Other means to assess the

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[4] Note, however, that a regulated pricing scheme is also considered as a market-based solution.

conditions of perfect competition include three pivotal supplier tests (Bowring & Josyula, 2015; SEDC, 2017), market share (concentration ratio), and a Herfindahl-Hirschman Index (Kemp, Forrest, & Frangos, 2018).

General approaches to enable higher liquidity and to improve market competition by means of small-scale resources are straight-forward. Basic steps include enabling aggregated or pool-based access of the resources to the market, allowing pool-based prequalification, increasing the frequency of market bidding & clearing or enabling participation of non-precontracted bids, minimizing minimum bidding size, increasing product resolution, relaxing technical constraints on the products (e.g., bid symmetry) (Poplavskaya, 2019). Similarly, the study in (EU-SysFlex, 2020) showed that by reducing the reserve procurement contract duration and increasing procuring reserve capacity frequency, the burdens of distributed energy resource (DER) participation could be alleviated, and cost savings generated. Furthermore, the market design shall guarantee sufficient visibility and predictability for SOs and FSPs. For the former, to have predictability about potential available reserves, and for the latter – sufficient certainty about revenues streams to support long-term investment.

## 2.4 MAYOTTE POWER SYSTEM

From a market perspective, the energy supply of the island is organized using a single buyer model presented above. The power system of Mayotte island is operated by electric utility Electricité de Mayotte (EDM). The energy landscape of Mayotte island faces many challenges of geographical islands such as a lack of interconnections, challenges to maintain frequency stability with high ROCOF, excessive cost of energy supply, must run/scheduled units with historical operations, multiple independent private suppliers with no centralized power markets, very few opportunities for market liquidity on the system services, and large amount of distributed generation.

### 2.4.1 Energy supply and demand

The energy supply of Mayotte island is provided by two thermal power plants with diesel generators, Longoni and Badamiers, as well as distributed solar photovoltaic (PV) plants connected to medium and low voltage networks. Longoni I (39,295 MW) and Longoni II (33.9 MW) are located on main Grande Terre Island, while Badamiers I (8.4 MW) and II (25.2 MW) are located on the smaller Petite Terre Island. The net production of these generators shall be corrected to the network and transformer losses of around 3.5% of their nominal capacity. Therefore, a total power available on the network for the Longoni power plants (I and II) and the Badamier power plants (G05 to G08 + Badamiers 2) can be estimated around 103.4 MW.

The total nominal power capacity of the distributed solar PV plants was 17.8 MWp in 2019. The estimated peak power of this capacity corresponds to about 75% of installed. There is a lucrative feed-in tariff (FiT) for small solar PV panels below 100 kWp. By 2021, the requested capacity for network connection reached 10.6 MWp (~110 installations between 36kVA and 100kVA).

Therefore, to the large extend, the electricity supply of the many islands comes from diesel generators that provide base and peak power supply as well as ensure system reliability. Such supply mix is extremely costly due to high fuel prices, and heavily carbon-intensive with more than 600 geq$CO_2$ per kilowatt-hour produced.

### 2.4.2 Future island development

Several installation projects are expected in the coming years. The additional solar PV plant installation for the tender application periods 2019-2020 is estimated to be 4 MW. Moreover, there will be 32 MW of solar PV with storage in tenders by 2025 in addition to the 3.8 MW that were installed until 2021. A total solar battery capacity released at peak hours would account for 16.8 MW assuming that solar PV + Storage installations participate in the peak for 40% of their installed power. Finally, a biogas power plant producing electricity from biogas of non-hazardous waste storage facility with an installed capacity of 1.07 MW should be put into operation in 2022 with an estimated production of 8 GWh/year.

Finally, Albioma power plant is currently under development in the port of Longoni and has a capacity of 12 MW (i.e., approximately 90 GWh/year). The operation of the power plant will be based on the use of imported biomass (approximately 70,000 tonnes of pellets per year, 2,000 t of local green waste). In addition, ENGIE is carrying out a combined cycle power plant project, also in the port of Longoni, with a capacity of 3x10MW or 2x16.5 MW using liquefied petroleum gas and eventually biogas.

# 3 METHODOLOGY

This chapter presents the methodology of the flexibility market design, including considered design scenarios, components of the desktop analysis, design criteria, use-case specific qualitative and quantitative assessment analyses, and feedback process interactions.

## 3.1 OVERVIEW

The methodology of the flexibility market and product design is presented Figure 3. The methodology can be decomposed into the following steps: *technical desktop analysis*, *literature review*, *use-case-specific qualitative and/or quantitative analyses*, *product and market composition*, and *utility and technology feedback* steps.

The high-level methodology of the flexibility market design is organized as follows. First, a variety of design solutions is examined with a desktop analysis that includes survey of technical characteristics of island systems, literature review, regulation review, and use case overview. To compare the advantages and disadvantages of the possible design options, both qualitative and (if possible) quantitative analysis are applied per specific use case. These analyses investigate the effect of design parameter on the desired auction or product functionality as well as overall design criteria. Given the results of these analyses, preliminary product and auction design of each use case is presented to the electric utility of Mayotte island, i.e., Électricité De Mayotte (EDM), and multiple questionnaires are prepared to receive necessary feedback. The design of the products and auctions is described based on the theoretical flexibility market framework presented in the following chapter of this report. Finally, ultimate design is derived based on the adjustments of the received feedback.

The outcomes of task T4.1 consist of the demo market design that will be used in the project demonstration activities, recommended market design solution that could potentially upgrade the demonstration market design in future, and elaboration on innovative design for geographical islands. In the following sections, a more detailed introduction to the methodology is given.

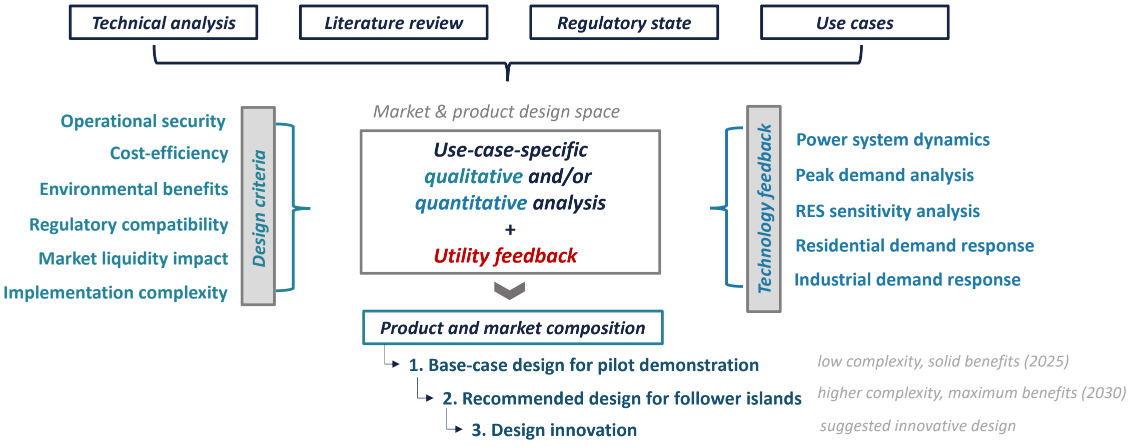

Figure 3: Methodology of market and product design

## 3.2 DESIGN SCENARIOS

Three design scenarios of the flexibility market are considered in this work are referred to as *EDM-BAU, FMTP-DEMO, and FMTP-FUTURE.*

***EDM-BAU*** design scenario describes the business-as-usual practices of electric utility on Mayotte island for operation management, i.e., use of own conventional generators and long-term tenders of flexible resources.

***FMTP-DEMO*** *is* a demo design that includes moderate modifications to the *EDM-BAU* design to enable market-based ancillary service procurement along with the traditional methods of vertically integrated electric utility. The demo design *FMTP-DEMO* is planned for the horizon of the project activities (year 2025) to gain tangible benefits without significant disruption of the existing electricity utility practices and considering the real-life constraints. In terms of planning horizon, the market design for demonstration aims to provide short-term procurement of flexibility.

***FMTP-FUTURE*** *is an* innovative design solution that outlines the ideal design in respect to the island context and design criteria. Although this design is expected to add more value, it also brings an additional level of complexity and IT infrastructure requirements that might be infeasible for the island environment as of today (e.g., small number of flexibility providers, low level of system monitoring capabilities, etc.). Therefore, the innovative solutions are recommended for the planning horizon of year 2030 and aim to combine the best design options.

## 3.3 Desktop analysis

The first stage of the methodology relies on desktop research to gather potential design options for all the use cases. The desktop analysis includes an assessment of the generic use cases, an overview of an energy policy and regulatory framework of the Mayotte island, an analysis of current methods for the ancillary services employed by system operator on the island, and information search about the ongoing and upcoming power system development on the island. In this analysis, the literature review focused on an analysis of the design options feasible for the specific product and market composition based on the current EU policy initiatives, previous European projects, and state-of-the-art solutions from academic research. The literature review for the frequency control included an examination of state-of-the-art practices for the organization of frequency control and regulatory guidelines. First, novel remuneration principles for the provision of system balancing services were reviewed. Subsequently, the EU-wide guidelines for the transmission system operation, electricity balancing, and internal electricity market were examined with a focus on the market and product requirements for the frequency stability ancillary services.

## 3.4 Design criteria

The evaluation criteria for the flexibility market and product design estimate how the design specification affects operational security requirements, regulatory compatibility with EU-wide guidelines and local regulation, socio-economic benefits of cost-efficient flexibility procurement, environmental benefits of flexibility utilization in terms of reduced carbon emissions, effects of the flexibility market design on the market liquidity and competition, and scalability to diverse island environments considering real-life implementation constraints. In the following the design criteria are explained in detail.

### 3.4.1 Operational security

The system operators shall ensure the operational security of system management with a prominent level of reliability and quality of electricity supply. This design criterion evaluates how certain design attributes affect the operational security in terms of risks to insufficient sizing of flexibility reserves, lack of available flexibility propositions, weak performance of the flexibility service providers, etc.

### 3.4.2 Cost efficiency

This design criterion aims to ensure the cost benefits of using flexibility services in comparison to the existing operational principles of vertically integrated utility. This criterion concerns a responsibility to ensure a cost-efficient flexibility sizing and procurement conditions. This criterion also partly concerns the issue of market power that the flexibility service providers can use to rise the market prices if no mechanisms are in place to prevent such actions.

### 3.4.3 Environmental benefits

The environmental design criterion evaluates the impact of design option on the carbon-intensity of operational management and supply mix. In practice, this criterion prioritizes the conditions that enable larger hosting capacity of renewable generation or minimize the use of carbon-intensive and inefficient generators.

### 3.4.4 Regulatory compatibility

Regulatory criterion evaluates the design options on the compatibility with EU-wide operational security requirements that are shaped by the regulation on ancillary services and affected also by grid code conditions. For instance, the requirements and principles of the system operation management, EU wide frameworks parameters for load-frequency control and reserves, and finally common principles for the procurement and the settlement of flexibility products are guided by the Commission Regulation (EU) guidelines presented in Table 2. Although these guidelines are not mandatory for island power system operation or can be incompatible with the conditions of vertically integrated electric utility structures, but they provide the reference point for best practices. Furthermore, national regulations and national grid codes describe the technical conditions and rules for connecting and operating a power generator or customer loads to the grid in diverse grid operating states.

Table 2: Regulatory documents relevant for flexibility market design

| Acronym | Name | Regulation Reference |
|---|---|---|
| **SOGL** | A guideline on electricity transmission system operation | (EU) 2017/1485 |
| **EMGL** | A guideline on the internal market for electricity | (EU) 2019/943 |
| **EBGL** | A guideline on electricity balancing | (EU) 2017/2195 |
| **DCNC** | A network code on demand connection | (EU) 2016/1388 |
| **GCNC** | A network code on requirements for grid connection of generators | (EU) 2016/631 |

### 3.4.5 Market liquidity and competition

The challenge of market liquidity is of primary importance for geographically isolated islands because it directly affects the market prices and social welfare. This challenge could be addressed by prioritizing the technology-neutrality of the design products and designing market mechanism that prevent conditions for exercising the market power.

### 3.4.6 Implementation complexity

This criterion measures the development, infrastructure, and management costs as well as the workload and required competencies of the personnel to enable the execution of a particular design option. Integration complexity to the business-as-usual methods of the electric utility is considered in the context of Mayotte power system.

## 3.5 QUALITATIVE AND QUANTITATIVE ANALYSES

The qualitative analysis was applied to the selection of the potential attributes of the flexibility market design, and it was complemented by quantitative analysis if both simulation tools and data were available.

### 3.5.1 Qualitative analysis

The qualitative analysis has been applied to stages of flexibility market design such as the flexibility requirement sizing (dimensioning), market bidding, market clearing, resource activation in real-time, and market settlement, including baselining requirements and remuneration principles. The evaluation principles for the qualitative analysis of the design options relied on the design criteria listed above. For instance, the methodology for the development of the voltage control market design solely relied on qualitative analysis because of a lack of detailed power system simulation model for Mayotte network. The qualitative analysis is provided based on the literature review of system operator practices for reactive power services and existing standards for voltage control.

### 3.5.2 Quantitative analysis

Two quantitative analyses have been applied to define the most suitable values for certain parameters of the frequency control and one quantitative analysis assisted in the use case of minimization of the peak consumption.

#### *3.5.2.1 Frequency control*

The quantitative analysis of primary frequency control products was carried out based on the simulations of Mayotte's power system dynamics model prepared in task T2.5. The tool is developed using SIMULINK[5] graphical programming environment, and the experiments are configured using MATLAB[6] platform and its programming language. The power system dynamics are analysed on a bulk-transmission grid level without considering network constraints. The experiment investigated the varying volume of Fast Frequency Reserve (FFR) and Frequency Containment Reserve (FCR) capacity required to ensure the frequency deviation does not exceed the allowed frequency nadir point (48.5 Hz) in the case of the largest generator or load loss (51.5 Hz). The reader is referred to deliverable D2.5 for more details on the scenarios, fault cases, and case studies.

Furthermore, the quantitative sensitivity analysis on the settlement period (1, 2, 4 hours) of the secondary frequency control product was carried out in task T5.1[7]. The analysis backtested the solar PV participation in the day-ahead capacity auction of downward automatic Frequency Reserve Restoration (aFRR) product through VPP. The backtests included such steps as day-ahead forecasting the solar PV production, bidding the capacity volume (<10% of MWp) at fixed price, simulating the market clearing (accepted/ not accepted bids), and market settlement. The analysis relied on the open data for actual and forecasted solar PV production, individual market bids, activated volumes and prices of aFRR product of Belgian TSO, Elia, due to the lack of data for the Mayotte island with sufficient granularity. Although the data of Belgian aFRR market is used, the general conclusions about the settlement period sensitivity shall also be applicable to the Mayotte because the analysis relies on the solar PV dynamics and forecast capabilities of the prediction models.

#### *3.5.2.2 Peak demand response*

Finally, for the development of peak DR product, quantitative research through a simulation methodology was applied. The objective of the simulation was to investigate how the peak load of diesel generators is affected by different strategies of battery energy storage systems (BESS) for peak demand reduction. The simulation relied on historical data of power production of diesel generators

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[5] https://www.mathworks.com/products/simulink.html

[6] https://www.mathworks.com/products/matlab.html

and solar power production available in half-hourly time intervals that constitute the overall demand of Mayotte island in 2020. The simulation was carried out for demand evolution scenarios in 2025 and 2030 according to the reference scenarios (EDM, 2019), which represent the base demand profile. Moreover, this base demand profile was adjusted by installed or planned to install resources on Mayotte island for peak DR. Two case studies were considered for each scenario (2025, 2030) of integration of these resources for the market analysis of day-ahead peak DR product in respect to the base profile: (i) a fixed-time peak reduction by BESS with 2, 3, 4, and 5 hour-long peak events and (ii) optimized-time peak reduction with mixed integer quadratic program (MIQP, i.e., mixed integer programs with quadratic terms in the objective function). The MIQP program is developed using an open-source Python-embedded modeling language for convex optimization problems, CVXPY[8], and the experiments are configured using Python programming language[9]. The simulations of the case studies were assessed with peak-above-limit metric that summarized the number of hours for which the demand exceeded certain threshold in percentage of the peak demand of yearly base profile.

## 3.6 FEEDBACK PROCESS

The feedback process was initiated after the preliminary composition for FMTP-DEMO design has been created. To obtain feedback from the electric utility on Mayotte island (i.e., EDM) and technical project partners, several webinars were organized that presented the available options for market design and preliminary selection of design criteria supported by the results of qualitative and quantitative assessment. Subsequently, questionaries were prepared in respect to the presented materials and provided to the electric utility. The final webinars were organized to discuss the feedback of the electric utility and select the final market design criteria for pilot demonstration. These decisions were considered by the technical partners that oversee flexibility management and trading platform.

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[8] https://www.cvxpy.org/

[9] https://www.python.org/

# 4 SYSTEM SERVICE SPECIFICATION

This chapter provides the description of system services that were defined in task T1.1 of MAESHA project in use cases on of “Frequency control”, “Voltage control”, and “Minimization of the peak consumption”. The description of system service outlines the technical scarcity it solves, theoretical description of the service and product classification, overview of the state-of-the-art products, potential service providers, current practices of the electric utility on Mayotte island to address the technical scarcity, and objective of the use case in MAESHA project. In what follows, the descriptions of these services are provided.

## 4.1 LOAD-FREQUENCY CONTROL

This section summarizes the information about the load-frequency control service in the context of the current project.

### 4.1.1 Technical scarcity

The operational security of the island power systems is guaranteed by the balance between the system supply and demand that is measured by the system-wide frequency at every point in time. A nominal frequency value (50 Hz in Europe) is required for devices to operate efficiently. While small frequency deviations are not critical for the system operation, large deviations (e.g., caused by forced generator outage or other disturbance) can lead to undesired load curtailment and even cascading grid collapse. Part of the power SO’s responsibilities related to system operation and planning is to guarantee the frequency stability in response to unexpected supply-demand imbalances. The most critical imbalances are caused by the faults leading to the disconnection of generation power plants or interconnection links, e.g., lines between island archipelagos, and are referred to as contingency events or reference incidents.

The frequency control of island power systems is often provided by diesel generators owned by the state utility. However, with many islands utilizing the high potential of RES, a rising share of inverter-based wind and solar generation partly replaces diesel generators, which leads to a reduction of the ratio of spinning machines in the system, which in turn has a negative impact on the synchronous inertia and Rate of Change of Frequency (RoCoF). Furthermore, stochastic nature of variable renewable generation introduces additional forecast uncertainty into the system operation management. The intermittency and forecast uncertainty of renewable generation will lead to a more frequent, faster, and/or longer ramps in net system load. These net load ramps will place more burden on the secondary reserves and, if they are inadequate, will also activate the primary reserves. Thus, the primary reserves may be depleted and therefore incapable of arresting and stabilizing frequency following the sudden contingency event (Eto, 2010). Such conditions can lead to a system blackout. Therefore, the frequency stability of island systems is endangered by the low inertia conditions and forecast uncertainty of renewable generation.

### 4.1.2 Service description

Load-Frequency control is a chain of integrated complementary frequency stability ancillary services aiming to retain, recover, and restore the grid frequency to its nominal value following supply-demand imbalance or large contingency event. The types of service can be categorized as the inertia response and a set of primary, secondary, and tertiary response levels of the control chain, and emergency control. Load-frequency control services are provided by the SO or procured from BSPs to compensate for the occurred imbalance with activation of active power capacity reserved for such needs. The task of the SO is to design, implement, and manage the provision of ancillary services in economically efficient and feasible manner.

### 4.1.3 Product categorization

The load-frequency control is carried out by the operating reserves and the synchronous inertia of rotating generators (and/or virtual inertia simulated by the inverter-connected resources) that maintain the system frequency stability within an acceptable operational range. The frequency control chain consists of the following services schematically illustrated in Figure 4 that illustrates the process of containment the frequency deviation in a frequency nadir point and following frequency restoration to the corresponding frequency value:

- Inertia Response
    - Synchronous Inertial Response
    - Virtual Inertial Response
- Primary Frequency Control
    - Fast Frequency Reserve (Response)
    - Frequency Containment Reserve (normal and disturbance)
- Secondary Frequency Control
    - Frequency Reserve Restoration (automatic)
- Tertiary Frequency Control
    - Frequency Reserve Restoration (manual)
    - Replacement Reserve
- Emergency Control
    - Under Frequency Load Shedding

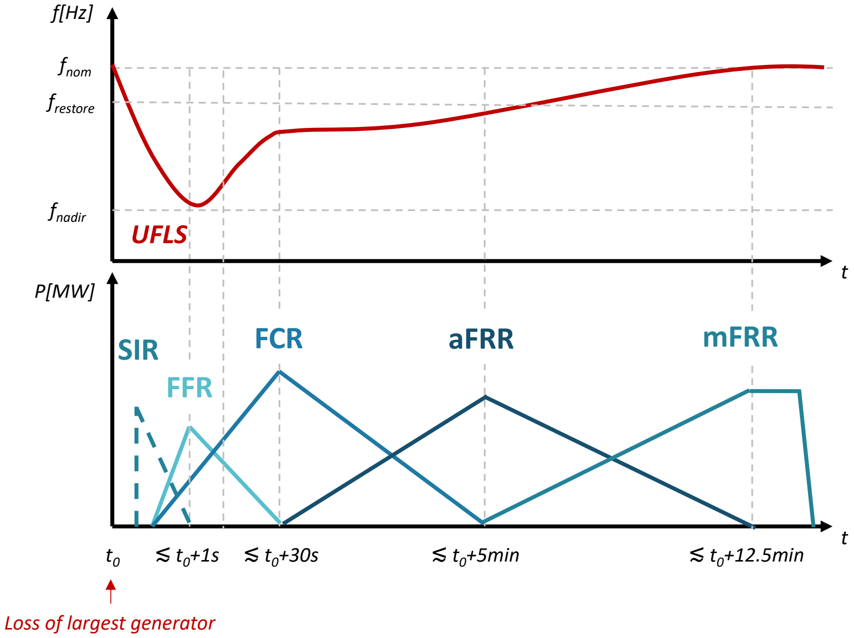


Figure 4: Frequency response products

In addition, the load damping phenomena causes inherent change in the load with the frequency deviation. For instance, as frequency drops, speed of motors decreases, and the motors withdraw less energy. Typically, this value is within 1—2% for most of the systems (ENTSO-E, 2009).

#### *4.1.3.1 Inertia Response*

Synchronous Inertia Response (SIR) is an inherent action of the rotating synchronous machines to frequency deviation that prevents fast frequency variations shortly after a power imbalance. The synchronous inertial response of the synchronous machines creates an active power transfer when the grid frequency deviates below or above the internal frequency/speed of its spinning mass. The amplitude of the power transfer is proportional to the phase angle between the grid voltage source and the electro-mechanical voltage source. Similarly, virtual inertial response can be provided by grid forming inverters that simulate the internal frequency/speed of its spinning mass and produce active power transfer based on the phase angle difference between the voltage source and the power-electronic voltage source. The virtual inertia constant of the inverter control algorithm is a parameter that can be adjusted to gain control over the inertia response. The value of the inertial response is in reducing the ROCOF following a power imbalance.

#### 4.1.3.2 Primary Frequency Control

Fast Frequency Reserve (FFR) product also deals with the issue of declining system inertia but employs a grid following inverter control. The reason for using a fast response is that when the system inertia is low, the quicker response allows less power (and therefore less reserve capacity) to contain frequency after a reference incident. This fast frequency response service provides automatic active power injection or load reduction aiming to reduce the initial ROCOF and point of the maximum frequency deviation, i.e., frequency nadir, following a contingency event. The response activation criteria of FFR product are distinguished among the *proportional response* to measured absolute frequency deviation or calculated ROCOF and *proportional response* to measured absolute frequency deviation or calculated ROCOF.

Frequency Containment Reserve (FCR) product corresponds to a type of primary frequency response service that provides an automatic active power injection/ absorption proportional to the locally measured or observed system frequency deviations due to minor supply-demand imbalances or contingency events. The aim of this service is to react within a few seconds to contain the frequency deviation below the required frequency nadir point and stabilise it to a steady-state value. The frequency response of traditional synchronous generators is organized by governor controls with droop characteristic, also known as frequency-watt control or frequency droop control. The idea of governor control is to adjust the output power of generator based on the locally measured AC grid frequency signal in a stable manner, i.e., following the droop curve response, to return the frequency to the normal operating range.

The crucial difference between the FCR products is in response time, droop rate, and dead band. The response time is the time required for a resource to reach 90% of the required response power resulting from a frequency deviation. A droop rate indicates the proportion in the inverter power changes of its power rating in response to a frequency change. For instance, a droop rate of 5% requires 100% power response to 5% change of the nominal frequency. Finally, the dead band defines the area of frequency deviation that requires no frequency response activation. The droop control response defines the change in power output from controlled power units (mostly generators) can be formulated as follows:

$$P^{gov}(t) = -P^{cap} \cdot \underbrace{\frac{\frac{\Delta f(t)}{f^{nom}} - \frac{DB}{f^{nom}}}{K - \frac{DB}{f^{nom}}}}_{Droop\ Gain},$$

where frequency deviation and dead band are defined by

$$\Delta f(t) = (f(t) - f^{nom}),$$
$$DB = \begin{cases} DB^{min} < 0, & \Delta f(t) < 0 \\ DB^{max} > 0, & \Delta f(t) \geq 0 \end{cases}$$

#### 4.1.3.3 Secondary Frequency Control

Secondary frequency control service is represented in Europe by automatic and manual Frequency Restoration Reserve (FRR) product that maintain the power balance and nominal frequency. The aFRR product operates using supervisory control and acquisition (SCADA) systems that poll sequentially for electric system data, with a typical periodicity of four seconds, and send the dispatch automatic generation control (AGC) commands to the RPUs/RPGs within a timeframe of tens of seconds to minutes. The aFRR's activation optimisation function (AOF) determines the bids that are activated. According to System Operator Guidelines (SOGL) Article 143, the goal of aFRR for a single area system like island is to regulate the frequency deviation towards zero within the time to restore frequency. For multi-area system the aim of aFRR is first to progressively replace the activated FCR reserves following the contingency event to restore the frequency from the steady state to nominal value of 50 Hz within the restoration time. In normal state, the secondary reserve restores the power balance by compensating for the forecast errors and system supply-demand variations of the agreed scheduled operation plan within the dispatch interval.

In terms of system control, primary response acts as proportional (P) controller to frequency deviation, while secondary control has a proportional-integral (PI) controller behavior to Frequency Restoration Control Error (FRCE), see Figure 5. The FRCE is defined by the frequency deviation for a single synchronous area (i.e., frequency control mode), as correctly represents the difference between the supply and demand, and by area control error in the case of multiple zones that considers frequency and power control errors of tie lines (i.e., normal control mode). The response is corrected for the frequency bias (MW/Hz) that considers *frequency sensitive load change (D) and primary reserve regulation (1/R)* as well as a measurement error $\varepsilon_{meter}$:

$$FRCE = B(f_{act} - f_{nom}) - \varepsilon_{meter},$$

where

$$B = \frac{1}{R} + D$$

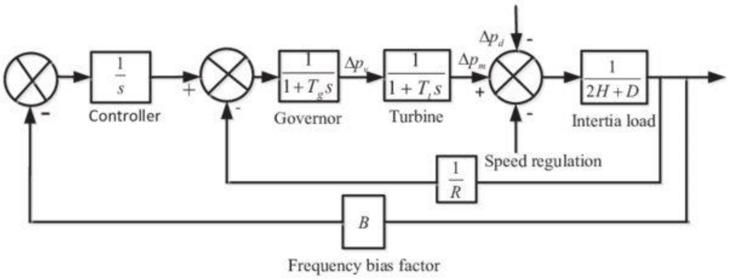


Figure 5: Primary and secondary control for a single area system (Sambariya & Nath, 2016)

#### 4.1.3.4 Tertiary Frequency Control

The tertiary control is normally implemented through manual FRR (mFRR) and Replacement Reserve products in Europe. These services compensate for the intra-interval generation and load variability as well as restore the FCR and aFRR reserves after the contingencies and assist the return of frequency to nominal values if secondary reserves are not sufficient. These services are deployed via manual dispatch actions of SO.

#### 4.1.3.5 Emergency Control

Finally, the emergency control is performed through automatic Under Frequency Load Shedding (UFLS) in response to a large uncontrolled frequency deviation. The UFLS is triggered when reaching the threshold frequency value. This service disconnects distribution feeders with the aim to prevent the risk of cascading faults. Ideally, the advanced DR programs could be used as a substitute to the UFLS to achieve the same effect. UFLS is commonly used on islands as a business-as-usual method for normal frequency control and not emergency control. Although the UFLS is effective in the arresting of frequency decline, it is a measure of last resort because it interrupts the electricity supply of customers reducing the quality of service. Furthermore, when the significant share of solar PV penetration is connected to distribution network, the efficiency of UFLS is reduced and can even worsen the situation during the contingency event. Low frequency nadir point can also trip legacy solar PV plants that operate at limited frequency fault-ride through settings.

### 4.1.4 Potential service providers

The challenges of the innovative frequency control for geographical islands are related to the identification of market mechanisms to incentivise frequency-response reserve provision from alternative flexible sources different from diesel generators. For instance, the reliability of island systems can be effectively provided by industrial demand response (DR), renewable energy resources (RES), residential DR managed by virtual power plant (VPP), smart charging of electric vehicle (EV) and vehicle-to-grid (V2G) technology, utility-scale Battery Energy Storage Systems (BESS), and power-to-hydrogen systems.

To solve the lack of inertia issue, flywheel energy storage systems can provide the virtual inertia and frequency support. Compared to batteries, flywheels have a much longer lifetime and higher power density. By regulating the speed of the flywheel in proportion to the grid frequency, the flywheel serves as an energy buffer that absorbs and releases its kinetic energy to provide inertia support. The inverter-connected resources are also capable to provide a virtual inertia response over noticeably short durations of up to a few seconds.

Typically, the primary and secondary controls are implemented by the conventional generators (spinning reserves) controlled by the generator’s governors that are capable to respond to the disturbance in the range of seconds. However, many inverter-based RES and DERs can provide frequency-watt control and proportional share the frequency response with the conventional generators. The newly updated IEEE Standard 1547-2018 requires all DERs to be capable of frequency-watt control for both over frequency and underfrequency events (Hoke, 2021). The studies of the frequency droop control by DERs (solar PV and BESS) in the Hawaiian island power system of Oahu showed that this control can improve the Oahu frequency response for both overfrequency and underfrequency events. Nowadays, the inverter-connected large-scale PV plants have been demonstrated to provide fast (sub-second) response, frequency-watt response, automatic generation control (aFRR), and voltage control on the islands of Puerto Rico (IEA, 2021).

The functionalities of frequency droop response, AGC response, and virtual inertia from technology mature wind and solar power plants can be mandatory part of the interconnection requirements of future utility-scale installations of inverter-based resources (GE Energy Consulting, 2012) as it would help system operators to improve reliability of supply. However, this might not be the requirements for the already installed plants due to the existing contracts or lack of technical capabilities, but such upgrade should be considered.

### 4.1.5 Product examples

This section presents state-of-the-art products available for frequency control services.

#### *4.1.5.1 Inertia and Fast Frequency Response*

A review of FFR grid standards, projects, and technical issues is available in an article of (Meng, 2019). An example of FRR product is Fast Frequency Response by the Electric Reliability Council of Texas (ERCOT) that operates the Texas's electrical grid. This product limits the maximum full activation time to 0.5 seconds and requires 10 minutes of sustained response. This service is meant for load resources with under-frequency relays and energy-limited resources like batteries. TSO in Ireland, EirGrid, procures Fast Frequency Response service that requires response within two seconds, but there is a premium payment for response within 0.15 seconds.

#### 4.1.5.2 Primary Control

The droop-based response is a fundamental property of modern frequency response products, e.g., a set of Dynamic Containment, Dynamic Regulation, and Dynamic Modulation products in United Kingdom that require activation time from 1 second to 10 seconds and sustain delivery for at least 15 minutes at full output.

#### 4.1.5.3 Secondary Control

On islands, the secondary operating reserves are rarely used due to its complexity (IRENA, 2018). One example of this product is applied on Hawaii islands (GE Energy Consulting, 2012). Fast FRR (up and down), which can be provided within a time of 1 min, is currently implemented by Greek TSO for procurement of reserves from hydro units.

#### 4.1.5.4 Tertiary Control

Tertiary Operating Reserve 1 procured by EirGrid in Ireland has activation requirement of less than 90 seconds (EU-SysFlex, 2019).

#### 4.1.5.5 Emergency Control

There are examples of procuring voluntary UFLS for customers with DR capabilities under interruptible tariffs. The service allows to curtail the customer loads at higher frequency than involuntary UFLS and use their capacity as fast reacting reserve in the case of a contingency even. The examples of such products exist in EirGrid (EirGrid, 2020) and ERCOT (Eto, et al., 2010).

### 4.1.6 Current experience on Mayotte

On Mayotte island, the balancing of the supply and demand in the grid is organized via a hybrid ‘primary reserve’ service that is analogous to a combination of Frequency Containment Reserve (FCR) and Frequency Reserve Restoration (FRR) services applied on the mainland. The operational frequency range supported by the primary reserve service is within a bandwidth ±0.3 Hz from the mean frequency of around 50.15 Hz. This exemption to operate the grid at a higher frequency has been granted to EDM by French Energy Regulatory Commission (CRE). The normal operating grid frequency is deliberately set above 50 Hz to avoid reaching low frequency thresholds leading to the UFLS. The primary reserve is provided by the droop control of the operating diesel generation sets of Longoni and Badamiers. Under this control, the generators are operating at the reference set-point of their maximal capacity and adjust their output with 4% droop to control the frequency. The reserved net capacity or headroom of the generators is the difference between the maximum power and operating reference point. The droop rate of 4 % means that the generator changes its power output by the nominal power for the frequency change of 4 % (i.e., 2 Hz). The UFLS control consists of 4 stages that are activated at 48.5 Hz, 48 Hz, 47.5 Hz, and 47 Hz, each disconnecting a 20 kV feeder with around 20% of total island load.

The Mayotte island has no interconnection to the neighbouring islands, so all frequency response must be provided locally. The reserve requirement sizing is based on the N-1 criterion that is a loss of the largest generation. Although it is necessary condition of frequency stability, it may not always be sufficient to cover the loss of the largest group because of the changing generation mix affected by the renewable generation. The main sources of potential contingencies on the Mayotte island are in the high voltage line (7.5 km of 90kV line) tripping connecting centralized production site (Longoni) to the place of maximum consumption (the capital of Mamoudzou), as well as disconnection of Badamiers generators. The procured reserve capacity is approximated to the 15 to 20% during the day and 10 to 15% at night (typically, below 8 MW), and it is significantly higher than the corresponding requirement for continental Europe. The product resolution of the primary reserve equals to half-hourly settlement period. In the case of a reference incident, EDM operators manually start up reserve diesel generators to replace the activated ‘primary reserve’, hence providing manual Frequency Reserve Restoration (mFRR) commonly applied in continental Europe. The time of starting up generators is about 10 minutes.

To stabilize the frequency on the island and ease the penetration of renewable energy replacing diesel generators, the French Energy Regulatory Commission (CRE) in deliberation n°2019-230 has recently tendered a stand-alone utility-scale lithium-ion BESS installation projects in the French department of Mayotte. Total Solar with a project for 4-MW/2-MWh is used for the primary frequency reserve service to generate savings by freeing up capacity on the thermal groups.

### 4.1.7 Use case objectives

The main objective of the frequency control use case is to establish a framework for balancing services alongside the existing methods and assets used to stabilize the electricity grid of Mayotte island. According to the key performance indicators (KPIs) of the MAESHA project presented in deliverable D1.1, the target of the developed framework is to enable a reduction in the yearly duration of supply interruptions from 6.6 h/year/consumer to 2.2 h/year/consumer and narrow the frequency deviations in normal operating conditions from current [49.6; 50.6] to [49.8; 50.3] Hz.

In practice, these objectives should target the market-based procurement of fast reacting assets for the frequency control that would improve the frequency quality in normal operation conditions and prevent the system supply interruptions in the case of generator disconnection. In the case of islands, an additional volume of faster-reacting primary reserves may enable the diesel generators with the lowest marginal costs to operate closer to the nominal load which is also more efficient in terms of fuel consumption and overall electricity supply costs. For instance, a study on Irish power system concluded that 60 MW of fast-responding BESS could replace the response from 3 GW of synchronous generation (P.V. Brogan, 2016). The management of the use case processes is organized via FMTP.

## 4.2 PEAK DEMAND REDUCTION

This section summarizes the information about the peak demand reduction service in the context of current project.

### 4.2.1 Technical scarcity

Peak load, or peak demand, is defined as the maximum demand for energy during a given period, typically a day or a year (US Energy Information Administration, 2022). Growing population and spreading access to electricity on islands contribute to a rise of peak demand. Such situation complicates the responsibility of SOs to ensure the power system’s ability to supply electricity during the times of peak demand. In that case, SOs need additional *peak generation capacity* to guarantee the adequacy of supply to meet demand.

According to a reference scenario of long-term demand planning, Mayotte’s peak demand might double in a period of 10 years, from 2020 to 2030 (Électricité De Mayotte, 2019). Considering the increasing wealth of the Mayotte population, the growing number household appliances that are a priori mainly peak consuming (e.g., air conditioning, lighting, electric stoves, rice pots, or electric vehicles) are likely to increase the peak demand in the coming years at a rate faster than the total energy consumption on island (CRE, 2020).

### 4.2.2 Service description

The category of services that are organizing sufficient long-term *peak generation capacity* is referred to as adequacy services. In this study, we focus on the services that provide up-regulation capacity for a specific period of peak demand on a voluntary basis to guarantee system adequacy and optimize economic and environmental performance of the grid by avoiding the expensive start-up of polluting peak generators. In addition, the service can be used to mitigate potential issue of voltage or current congestion if locational information is given and leveraged. These services are provided by the Capacity Service Provider (CSP) to the island's SO. Peak demand reduction is typically organized through DR services that compensate end-use (retail) customers for reducing their electricity use or increasing local generation when requested due to economic or reliability reasons at peak time events.

### 4.2.3 Product categorization

The categories of DR products can be categorized *conditional* and *scheduled* based on the activation method for re-profiling that serve *reliability* (emergency) or *economic* goals.

#### *4.2.3.1 Conditional re-profiling*

A conditional DR assumes a reliability-based re-profiling of demand under condition of the reliability request from the SO to mitigate a critical peak demand event. The notification for the re-profiling is sent in real time and expects that the customer reduces the load or increases the generation within a certain time and will remain this reduction until the release notification is received. The activation can be automatic via direct communication link to site-installed controller/ switch or semi-automatically via text, email, or phone call. The trigger event can also be an underfrequency threshold in the case of emergency programs. This service typically provides *capacity payments* based on the obligated level of load reduction (e.g., monthly) and/or only *energy payments* for the actual reduced load during an event.

#### *4.2.3.2 Scheduled re-profiling*

A scheduled DR is organized as a scheduled economic-based re-profiling based on '*energy offer*' to reduce consumption at a participant bid price or fixed FiT price. In this program, the successful bids are compensated only for the actual energy reduction. The schedule of re-profiling is defined by the CSP in the bid or is assigned by SO. The energy payment can also be provided as an electricity bill credit in *peak time rebate* program. In this report, we focus on explicit DR products procured on the market, but application of implicit DR is also possible in the form of customer tariffs, e.g., time of use, critical peak pricing, and real time pricing. The implicit DR programs offer higher tariff rate during peak periods and lower tariff rate during off-peak periods to flatten the demand curve (Shariatzadeh, 2015).

### 4.2.4 Potential service providers

Peak capacity can be provided by installing centralized or distributed controllable generation capacity or, alternatively, mobilizing *demand-side flexibility* to perform similar up-regulation functionality offering either load shedding or load shifting. In MAESHA project, the planned providers of peak reduction include smart EV charging, behind-the-meter diesel generators, utility-scale BESSs, collective self-consumption of solar PV generation by the local energy communities, as well as residential and industrial DR providers.

On the Mayotte island, the accessible DR capacity had been estimated at nearly 1 MW on weekdays and 0.5 MW on weekends at the time. This capacity corresponds to the reduction in consumption related to air conditioning or food cooling that can be mobilized in large commercial areas or at the port of Longoni (refrigerated containers). For instance, the refrigerated containers enable trait to mobilize 650 kW of load shedding at peak hours. In addition, the optimized use of lifting gear in the port also offers load shedding potential. The duration of identified load shedding varies from 30 minutes to 2 hours depending on the sites. The other sources of flexibility could be a seawater desalination plant, airport facilities, port of Longoni (refrigerated containers, lifting facilities). Furthermore, the deployment of hydrogen electrolysers as controllable loads can increase demand side flexibility and provide grid balancing services.

### 4.2.5 Product examples

There are existing applications of DR programs, including the island power systems, that aim to cope with capacity adequacy issues. For instance, Hawaii electric company has a tariff structure that incorporates examples of reliability-based DR called Fast Demand Response Program and economic-based DR in Battery Bonus program.

Fast Demand Response Program of Hawaii electric company (Hawaiian Electric Company Inc.; Maui Electric Company, 2022) is intended for peak time events from 7 p.m. to 9 p.m. weekdays (excluding federal/state holidays) duration of a maximum of 1 hour with 10 minutes of event initiation time. The program has two tariffs depending on the number of peak time events. The program is intended for commercial or industrial customer able to commit a minimum of 50 kilowatts of DR capacity. It presumes a use of any non-essential process or equipment such as heating ventilation and air conditioning, non-essential lighting, etc. The program provides the monthly Nominated Load (capacity) Incentive (kW reduction) and the Energy Reduction Incentive (kWh reduction). The Event Performance Factor is used for the Nominated load.

Battery Bonus program (Hawaii Electric Company , 2022) provides bill credits for customers to add battery storage to an existing or new rooftop solar system with maximum PV size equal to twice the battery storage size. The customers are compensated monthly with a fixed *peak capacity payment* for the committed storage capacity and a fixed monthly *energy export credit*. The capacity is specified by Hawaiian Electric Company as the amount of kW daily discharged from the battery for firm two hours during the window of 6 – 8:30 p.m. including weekends and holidays.

Furthermore, Pacific Gas and Electric Company adopts a combination of the peak rebate time program and smart thermostat program is adopted (Portland General Electric, 2022). The smart thermostat program uses a *direct load control* of air conditioning, an electric forced air furnace or ducted heat pump units during a peak time event by temporarily reducing the temperature requirements to reduce energy use for 1 to 4 hours. This program presumes a sign-up and seasonal-based remuneration under condition to participate in at least 50% of events. The *peak rebate program* is intended for customers having no direct control units with activation by email and/or text before each event. The volume of energy reduction is measured as deviation from a baseline that is calculated using historical baseline methodology, i.e., delivered energy is calculated in respect to historical average consumption over the past 10 days for the same hours of the day as the peak time event. This excludes weekends, holidays, and any other past peak time event days.

Furthermore, the combination of reliability and economic-based demand response is implemented by New York Independent System Operator ( (Lamont, 2018). In Europe, a diverse of service exist for emerging congestion management services (Heilmann, 2020). Dispatchable DR is also recognized as explicit DR that is implemented in several EU countries (SEDC, 2017).

Finally, several bi-directional distribution network tariffs for residential and utility-scale BESSs were approved for trial by the National Electricity Market in Australia (Australian Energy Regulator, 2022). These tariffs encourage battery charging during a core sun soaker window, and reward battery's power export to the grid during nominated peak hours. The rewards are provided in the form of (critical) *peak tariff rebate*.

### 4.2.6 Current experience on Mayotte

EDM creates a production plan for diesel generators daily for 48 half-hourly settlement periods of the next day D. The plan for the diesel generators is created by EDM using the outcome of “Running program” solving security-constraint unit commitment and economic dispatch problem to cover the expected net demand (i.e., total forecasted demand minus forecasted solar PV generation) and provide required primary reserve. The generators are dispatched in merit order that includes base (i.e., continuously operating) generators, semi-base generators, and peak generators. Each generator group is assigned an operating power in percent of their nominal power capacity, typically 80 – 90% for base generators but lower for the semi-based and peak generators. The headroom above the operating point is used for the droop-based frequency response.

Currently, the load profile of Mayotte island has two peak demand periods: midday peak and evening peak. The midday peak, between around 8 a.m. and 5:30 p.m., is due to the industrial, administrative, and tertiary activity of the island and to the use of commercial air conditioning. The evening peak, between 6:30 p.m. and 9 p.m., is due to residential energy consumption related to domestic air conditioning usage and public lighting. The issue of system adequacy is currently addressed by EDM in a following manner: the peak demand is covered by start-up of low-efficient peak generators that are used as a strategic reserve. To prevent the use of peak diesel generators, EDM tendered Albioma’s 7.4-MW/14.9-MWh BESS for load shifting service on Mayotte island. The battery storages are remunerated for power supply at peak times with a FiT scheme.

### 4.2.7 Use case objectives

The goal of the use case “Minimization of the consumption peak” is to reduce the consumption peak by developing market-based solutions for load shifting, load shedding and activation of distributed generation behind the meter. Besides the total peak demand reduction, the use case also considers local peak reduction potentially tailored for the congestion management (e.g., overloaded medium voltage/low voltage transformers) that requires sufficient coverage of power flow monitoring in the distribution network which is commonly absent on islands.

The key performance indicators of MAESHA deliverable D1.1 suggest that the design solution of the peak demand reduction product shall contribute to a reduction of electricity supply costs by 10% and a reduction of peak demand by 15%. The desired outcome of the market design on a short-time scale is to help EDM in minimizing the cost for electricity supply and reduce $CO_2$ emissions by replacing peak diesel generators with sustainable energy resources. In addition, the market can assist EDM in decision-making regarding the potential time-off-use tariff on a longer time scale. A procurement of the developed products for peak reduction shall be organized on the FMTP along the frequency control.

## 4.3 VOLTAGE CONTROL

This section summarizes the information about the voltage control service in the context of the current project.

### 4.3.1 Technical scarcity

Voltage stability is one of the requirements of secure and reliable operation of the power system. The voltage level at all points of delivery should be equal to 230 V for single-phase power and at 400 V for three phase power in LV grid and equal to 20 kV in MV grid, with a margin of acceptability of [-10%, +10%], both in steady-state and transient conditions. In contrast to frequency control, the voltage levels are not system wide as frequency but localized to a specific system node. The location-specific nature of the voltage issues requires visibility of the network’s power flow parameters by the SO to apply the timely and effective measures. However, EDM has a limited visibility of the network only through real-time voltage measurements at the three HV/MV substations in the system. This creates challenges to detect voltage issues, to find assets that could effectively resolve these local issues, and to apply complex dynamic approach for voltage control. However, currently identified voltage issues on the island include low voltage levels at the end of long feeders, potential of transient overvoltage and resonant behaviour due to increase of reactive power level in the cabling system, and high voltage levels on 90 kV transmission lines during the low demand period from April to October.

### 4.3.2 Service description

Voltage services aim to ensure the maintenance of voltage within certain limits to stabilise the voltage in the event of an incident or to mitigate the risks of overvoltage or undervoltage. Voltage service provides an automatic active or reactive power injection/ absorption proportional to the locally measured or observed voltage deviations.

#### *4.3.2.1 Product categorization*

Common mechanisms of voltage control differ between voltage-active power mode, voltage-reactive mode, and power factor-active power mode. In the voltage-active power mode, the VPU shall control its active power as a function of voltage following a voltage-active power piecewise linear (Volt-Watt) characteristic. In power factor mode, the voltage is controlled by adjusting the power factor within the limits of capacitive (generation of reactive power to increase voltage) and inductive (consumption of reactive power to reduce voltage) modes. In voltage-reactive power mode, the VPU shall control its reactive power output as a function of voltage following a voltage-reactive power piecewise linear (Volt-VAR) characteristic. Other products can use fixed reactive power set-point or fixed power factor mode.

### 4.3.3 Potential service providers

The target VSPs of these services are BESS, RES-based VPPs, power-to-hydrogen system, and DR assets. Looking at the development of the Mayotte power system, with increasing number of solar PV plants often combined with BESS, the perspective direction of the voltage control is to mobilize the capabilities of these flexible resources for the voltage control service. A potential for innovation is to mandate the presence of voltage control (Volt-VAR) function in smart inverter-based generators in the connection agreement.

### 4.3.4 Product examples

From the market procurement perspective, the locational dependency of the product leads to a low liquidity condition, where the competition efficiency of the market-based procurement schemes is not guaranteed. In this case, bilateral agreements or mandatory service provision through grid code requirements are the default solution in Europe. In fact, in many European countries, the running generators are obliged to provide voltage regulation services to the TSO. Only in Belgium, MVAR service is procured entirely via a market based tendering procedure. However, even the mandatory services are remunerated with prices of the competent authorities or regulated price (€/MVARh). The price is defined by the active power losses (during the production of reactive power) and maintenance related to wear & tear caused by delivering reactive power regulation.

### 4.3.5 Current experience on Mayotte

On Mayotte island, EDM controls the voltage profile through manual activation of appropriate reactive power compensation devices, such as capacitor banks, manual and automatic tap-changing of transformers and control of the available diesel generators (Longoni and Badamiers groups). The generators operate in voltage-reactive power mode and Badamiers 1 in a power factor mode.

### 4.3.6 Use case objectives

The use case of voltage control aims to enable the deployment of flexibility resources connected to the distribution grid to ensure the voltage stability of island power system. Here, the voltage control product design is limited to the definition of parameters for voltage-reactive power control (although it can also be provided with active power measurement). For a pilot testing of voltage control, the EDM will identify a dedicated location in its system with specific voltage issues where flexibility of potential assets will be used to support EDM in their voltage control. In addition, EDM will provide the Volt-VAR control curves parameters required for the control.

# 5 FLEXIBILITY MARKET DESIGN FRAMEWORK

This chapter introduces the theoretical flexibility market framework that was used to design flexibility market in MAESHA project. The chapter starts with a general overview of the framework and continues with a detailed description of its components divided into *product specification* and *auction specification* each consisting of a set of stages with design attribute options.

## 5.1 GENERAL DESCRIPTION

The framework for the design of flexibility market is illustrated in Figure 6. The framework shows that the outcome of the market design is influenced by a set of exogeneous factors and underlying legal environment. First, the market design outcomes are constrained by the legal and economic environment it is developed in and hence are tightly linked to the energy market design. Second, the technical specifications for required system operation and available flexible resources provide the related requirements for the market design. Finally, the design criteria steer the development of the market design to a particular point of the design space.

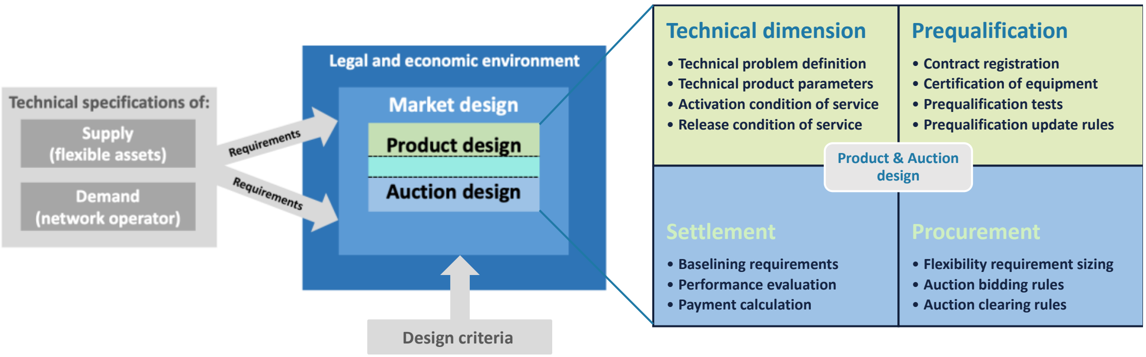


Figure 6: MAESHA flexibility market design framework. Adapted from (Heilmann, 2020)

The framework divides the task of market design into *product* and *auction* dimensions that consist of a set of stages with design attribute options. The product design describes the trading objects (e.g., technical good or service) that are traded on the market with a set of attributes, while the auction design structures the rules and mechanisms that enable trading process between the market participants to exchange flexibility products. Some of the design parameters are not trivial to distinct between the product and auction parts and no standardized approach exists yet. Here, we relate *the technical dimension* of the product and *prequalification* stage to the product design, while *procurement* and *settlement* to the auction design. Therefore, the product design describes the technical attributes of flexibility product and rules to assess the compliance with the minimum requirements.

The main aspects of the procurement stage of the auction design are related to flexibility requirement sizing, auction bidding, and auction clearing. The flexibility requirement sizing is a process of dimensioning minimum flexibility requirement that covers the needs of SO in a specific service. The auction bidding describes the structure of the bidding process including the attributes of bids (i.e., trading dimension of a product) and bidding rules. The auction clearing describes the winner determination process, i.e., how the supply and demand of flexibility are matched to select the successful bids and under which pricing mechanism. The settlement stage consists of requirements for baseline calculation, evaluation of the service provision, and financial payment. In what follows, we describe in detail the stages of the product specification and auction design.

## 5.2 PRODUCT SPECIFICATIONS

The product design consists of identification of a technical problem it mitigates, specification of relevant technical attributes of this product, definition of values for the attributes, and tests to validate the resource compliance with the declared attribute values. In what follows, we present the common technical attributes for flexibility products and corresponding prequalification process.

### 5.2.1 Technical attributes

In this market design framework, the categories of the technical attributes in the product specification are divided to general characteristics, timing of delivery, and communication parameters. The summary of common technical attributes is presented in

Table 3, and the parameters of response time are illustrated in Figure 7. Furthermore, some products include specific attributes for a response shape that define the type of response (e.g., parameters of voltage or frequency droop curves). These attributes are specific to each service type and hence are omitted from common technical attributes.

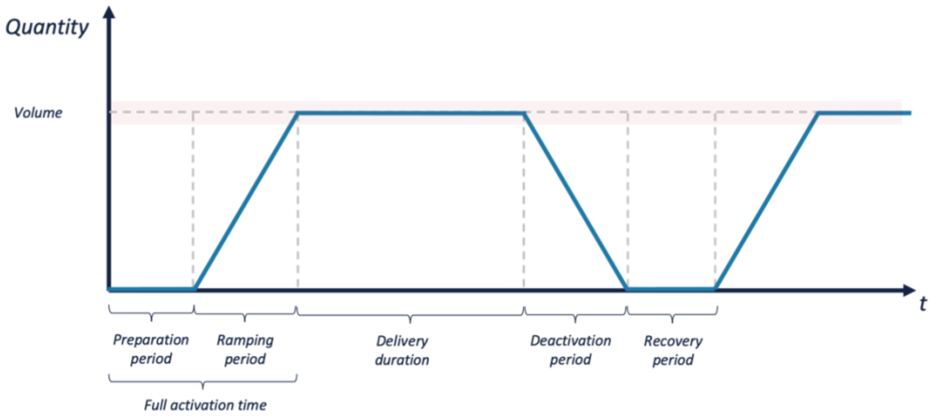


Figure 7: Technical attributes of response time for product specification

### 5.2.1 Prequalification

The prequalification process is a process of establishing legal contract for provision of ancillary services between the FSP and SO and verifying the technical capabilities of service provision and product volume of FSP. The volume is defined according to the technical product requirements and auction requirements to participate in the market. The prequalification process consists of *market prequalification* (that includes verification of compliance with financial requirements, contract registration, and communication testing), *product prequalification*, and *grid prequalification*. The *registration* is organized to establish a legal contract and verify compliance with metering requirements. The information that is required to be presented by FSP at the registration stage is shown in Table 4. Furthermore, documentation and certificates for metering and communication devices described in Table 5 are required. The *communication prequalification* test is organized to test and verify the technical capability of the flexibility service provider to successfully perform required information exchange with the market platform. The *product prequalification* tests are organized to test and verify the technical capability of FSP to comply with the procedure for offering and delivering the service and to deliver an offered volume according to product and market requirements. Finally, the *grid prequalification* tests are necessary to verify that FSP can deliver the service with the prequalified volume without causing abnormal operating conditions to the system (INTERRFACE, 2022).

Table 3: Technical attributes of product specification

| Attributes | Units/Options | Description |
|---|---|---|
| **General characteristics** | | |
| **Product type** | Capacity<br>Energy | Determines if it is power availability-based product or power activation-based product |
| **Location required** | (Y/N) | Determines if the locational information is needed |
| **Non-tripping range** | Hz | Determines the frequency operating range of the FPU or FPG |
| **State-of-charge management** | (Y/N), type | Determines if state-of-charge energy management is allowed and how |
| **Aggregation allowed** | (Y/N) | Determines if resource aggregation is allowed |
| **Symmetric product** | (Y/N) | Determines if symmetric product is allowed |
| **Asymmetric direction** | Upward<br>Downward | Direction of allowed regulation |
| **Response time** | | |
| **Maximum preparation period** | Seconds | Time between receiving the activation signal and actual start of activation |
| **Maximum ramping period** | Seconds | Time to reach the requested activation volume after start of activation |
| **Maximum ramping** | MW/seconds | Change in power activation from one time unit to the next |
| **Maximum full activation time** | Seconds | Time between receiving the activation signal and full delivery of requested volume |
| **Minimum delivery duration** | Minutes | Continuous time of full delivery at the requested volume |
| **Maximum deactivation period** | Seconds | Time to reach the baseline set point from full delivery of the requested volume |
| **Maximum recovery period** | Hours | Time between the end of deactivation period and the following activation |
| **Post-fault delay for recharge** | Minutes | Time to delay a recharge after the fault |
| **Communication** | | |
| **Mode of activation** | Automatic<br>Manual | Mode of activation control |
| **Activation type** | Centralized<br>Decentralized | Type of activation control |
| **Activation signal** | Frequency<br>Voltage<br>FRCE | Type of measurement signal used for activation |
| **Ramp activation signal** | Continuous<br>Step-response | Type of set-point activation signal |
| **Activation scheme** | Pro-rata<br>Merit order | Type of activation of energy bids |
| **Activation cycle** | Seconds | Time of communication cycle |
| **Data aggregation level** | FPU<br>FPG<br>FSP | Level of direct communication between flexibility provider and market/ SO platform |

Table 4: Flexibility service provider registration information

| Description |
|---|
| Flexibility Service Provider ID |
| List of Delivery Points |
| Name of the Delivery points |
| European Article Number of the delivery point |
| Grid User contract/ declaration |
| Location of the assets (Site address) |
| Voltage levels and connection points |
| Type of active power reserves |
| Technical characteristics of delivery points |
| Information on combinability with other products |

Table 5: Flexibility service provider technical information

| Description |
|---|
| Type of measurement device |
| Location on the electrical grid of the measurement device, meter’s certification |
| Remote terminal unit technical info and commissioning test if applicable |
| IT protocols |
| The accuracy of the measurement chain |

#### 5.2.1.1 Product prequalification tests

The aim of product prequalification test is to validate the baseline methodology, to deliver the timing parameters of FPU/FPG’s response, to measure the prequalified volume of FPU/FPG, and to validate communication delays. A set of possible prequalification tests for considered products is provided in Table 6. Furthermore, the product prequalification approaches for FPGs can be categorized to *pool-based testing*, *individual unit testing*, and *type-based testing* as described in Table 7. Type approval and pool-based prequalification significantly ease the prequalification of flexibility providing groups. In any type of prequalification, SO has a right to request real time data and history data separately of the individual FPU of FPG for settlement purposes. The conditions for prequalification can arise because of the conditions stated in Table 8. Furthermore, in case of delivery points using private measuring devices, system provider will evaluate during the delivery point acceptance procedure the precision class of the service provider’s measuring chain by considering the worst precision class value amongst the measuring chain components (current and voltage transformers, measurement equipment). The real-time monitoring is needed to verify the availability of FPU or FPG to perform the allocated system service.

Table 6: Prequalification tests for frequency control product

| Test | Description |
|---|---|
| **Power Ramp** | Assesses the FPU/FPG’s ability to deliver the required power ramp within the full activation time, *upward/downward* or *bi-directional* |
| **Live Power Setpoint** | Assesses the FPU/FPG’s response to system operator setpoint in a live environment |
| **Communication** | Assesses the FPU/FPG’s control communication and time of information exchange with SO/FMTP platform |
| **Baseline** | Assesses the compliance of baseline quality over a given period with minimum quality requirements |
| **Step Response** | Assesses the FPU/FPG’s ability to deliver the required response in steady state at discreet activation signal deviations over the operational range within the allowed tolerance (e.g., 3%) |
| **Ramp Response** | Assesses the FPU/FPG’s ramp rate at the required response time (including measurement time and instruction time) in the case of a steadily increasing frequency deviation |
| **Duration** | Assesses the FPU/FPG’s ability to sustain full response during the minimum delivery duration at maximum deviation |
| **Frequency Measurement** | Assesses the quality of frequency measurements that the unit supplies to the frequency control |
| **Frequency Sweep** | Assesses the FPU/FPG’s performance against a varying frequency over the entire performance envelope |
| **Live Frequency** | Assesses the FPU/FPG’s response to frequency deviation in a live environment |

Table 7: Prequalification tests of Flexibility Providing Groups

| Group testing type | Description |
|---|---|
| **Pool-based** | FPG is tested as a whole |
| **Individual unit** | Each FPU is tested separately |
| **Type approval** | FPU of prequalified type can be added to the FPG without prequalification tests |

Table 8: Conditions for prequalification tests

| Condition |
|---|
| **at a regular intervals** |
| **in case of changed in technical or availability requirements or the equipment** |
| **in case of modernization of the equipment related to the flexibility activation** |
| **in case of the deteriorated service performance** |
| **In case of the increase in the service capacity** |

## 5.3 AUCTION SPECIFICATIONS

In this section, the auction design process of the flexibility market design framework divided into the flexibility procurement and settlement stages is described for system balancing, peak demand, and voltage products.

### 5.3.1 Flexibility procurement

In what follows, this report presents the description of the flexibility procurement stages within the proposed market design framework.

#### 5.3.1.1 Flexibility requirement sizing

The flexibility requirements sizing is the operation carried out by the system operator to dimension the Minimum Flexibility Requirement (MFR) to be contracted in advance or in real time to mitigate power system's technical scarcity. Table 9 defines the attributes of the flexibility sizing.

Table 9: Parameters of flexibility requirement sizing

| Attribute | Design space | Definition |
|---|---|---|
| **Sizing frequency** | Static | A temporal resolution of flexibility sizing |
| | Seasonal | |
| | Dynamic | |
| | Hybrid | |
| **Sizing methodology** | Heuristic | A method used to assess MFR |
| | Deterministic | |
| | Probabilistic | |
| | System Simulation | |
| | System Conditions | |
| **Sizing target** | Prevent power outage | An objective of MFR's sizing in respect to power system's technical scarcity |
| | Prevent UFLS | |
| | Intra-period imbalance | |
| | Peak demand | |
| | Peak-to-average | |
| **Sizing variable** | Historical imbalance | A type of event/parameter used to assess the sizing target |
| | Reference incident | |
| | FRCE | |
| | Forecasted imbalance | |
| | Historical peak demand | |
| | Forecasted peak demand | |
| **Sizing resolution** | ½ hour | A temporal resolution of sizing variable |
| | 2 hours | |
| | 4 hours | |
| | 24 hours | |
| **Sizing convolution** | Maximum | A type of function to combine different sizing variables |
| | Probabilistic | |
| **Sizing reliability** | % | A level of reliability that is guaranteed by the sizing method |

Sizing frequency and resolution

The frequency of flexibility sizing can be categorized as *static*, *seasonal*, *dynamic, and hybrid*. Under the static and seasonal frequency, the required flexibility capacity is calculated over long term, e.g., annually, or seasonally, at the sizing temporal resolution. In the case of dynamic frequency, the MFR is updated regularly, e.g., daily or weekly, based on the expected short-term system conditions and associated risk for system technical scarcity. Hybrid sizing combines static and dynamic sizing frequencies.

The resolution of sizing is often linked to the sizing frequency. Here, a range of resolution options varies from a minimum of half an hour period that corresponds to the dispatch time unit on Mayotte island to maximum of 1 day.

Sizing variable

For the balancing services, the aim of the flexibility (or reserve) sizing is to estimate the *Minimum Reserve Requirement* for upward reserves that compensate for power deficit and downward operating reserves that minimize power surplus in real-time in response to sudden demand-supply imbalances. The main independent sources of imbalances include (i) the generation unit or relevant transmission assets outages; (ii) the error between the forecasted load and its realization; (iii) the error between the forecasted renewable generation and its realization (Cauwet, 2019). Therefore, the sizing variables can be the historical system imbalance, a reference incident, FRCE, or individual imbalance drivers (production and demand forecast errors), or imbalance variations between the settlement periods. For peak demand reduction, such the sizing variables correspond to historical or forecasted peak demand. For peak demand reduction, such the sizing variables correspond to historical or forecasted peak demand.

#### Sizing methodology

The sizing methods are classified to *heuristic*, *deterministic*, *probabilistic*, *system simulation,* and *system condition* methods following methodologies available for sizing *Minimum Reserve Requirement (MRR) of frequency control services*.

For instance, the traditional heuristic sizing method for aFRR product is empiric noise management approach that depends on the maximum anticipated consumer load for the control area. The deterministic sizing defines the minimum reserve requirement based on N-1 criterion of a reference incident, i.e., the largest possible generation or consumption incident (e.g., generation units or sets, interconnection-links, power infeed on single busbar). However, the loss of the largest generating unit can be neglected due to economic reasons, and then the risks of the generator loss are treated with UFLS. Overall, there is a trend to gradually move from deterministic practices that rely on the N-1 criterion toward probabilistic methods because the former cannot handle the uncertainty of renewables. Moreover, a reference incident might not be a sufficient condition for small-scale system with varying inertia levels (e.g., when diesel generators are replaced by RES). The probabilistic sizing determines the total required reserve to cover the imbalance risks with the sizing reliability of 99% of the time. For instance, Graf-Haubrich approach calculates the necessary control reserve considering convolution of independent power imbalances like power plant outages, load variations, schedule step error, and forecast error (Maurer, 2009). A modification of this method with sizing day-ahead for a product length of 1 hour can be found in (Jost, 2015). The simulation methods can determine the outage risk by means of a Monte Carlo simulation, in which a probability density curve of the outages is found based on day-ahead schedule of generating units and interconnectors. The simulation methods can determine the outage risk by means of a Monte Carlo simulation, in which a probability density curve of the outages is found based on day-ahead schedule of generating units and interconnectors.

Finally, *system condition* methods include the methodologies that consider expected system state to determine the reserve requirement, typically dynamically. For instance, clustering and regression approaches can be used to map historical FRR needs to the current system conditions (ELIA, 2020). Another innovative methodology explores sizing of FCR as a function of grid parameters such as inertia and load damping as well as dynamics of the potential providers (Jomaux, 2016). A linear programming program selects those providers that guarantee least cost service portfolio that fulfils static and dynamic constraints. The latter are obtained based on the discretization of the swing equation and on a relatively simple characterization of the FCR reaction.

#### Sizing convolution

The total volume of flexible reserves can be calculated using a maximum of all risks (optimistic), their sum (pessimistic), or probability of simultaneous occurrences of both risks (IRENA, 2018).

#### *5.3.1.2 Flexibility procurement*

The flexibility procurement is the operation carried out by SO to contract the flexibility from FSP to fulfil MFR. In market terms, SO is a single buyer or auctioneer that is organizing monopsony procurement auction, i.e., auction with a single buyer). Table 10 describes the attributes of flexibility procurement used in present flexibility framework.

Table 10: Attributes of flexibility procurement

| Attribute | Design space | Definition |
|---|---|---|
| **Procurement frequency** | Static | A temporal resolution of flexibility procurement |
| | Seasonal | |
| | Semi-dynamic | |
| | Dynamic | |
| | Hybrid | |
| **Procurement scheme** | Voluntary | A type of arrangement between the flexibility provider and auctioneer |
| | Mandatory | |
| **Procurement mechanism** | Competitive Auction | A type of financial compensation for the service procurement |
| | Bilateral Agreement | |
| | Regulated Tariff | |
| | Interconnection Condition | |
| | Service Compensation | |
| | Hybrid Tariff Compensation | |
| | Hybrid Tariff Competition | |
| **Contract duration** | 1 day | A temporal period for which the flexibility is procured |
| | 1 month | |
| | > 1 year | |
| **Contract resolution** | ½ hour | A length of temporal period for which the flexibility is procured |
| | 2 hours | |
| | 4 hours | |
| | > 3 hours | |
| | 24 hours | |

### Procurement frequency

A temporal resolution of procurement stretches from *dynamic* daily procurement to *semi-dynamic* (weekly), *seasonal* (4 months), and finally *static* (yearly) frequency. A hybrid procurement combines static and dynamic approach.

### Procurement schemes and mechanisms

The procurement schemes and mechanism are listed here in the order from the most regulated to the most competitive. *Condition of Interconnection* assumes mandatory provision of service as a condition for a network connection. This mechanism considers that the costs of the service provision are implicitly covered by the energy prices. *Regulated Tariff* considers fixed remuneration for service provision. The value of the regulated tariff is calculated based on the SO's expenditure cap and volumes required for the services. The regulated tariff is typically set for a long-term period and can provide more revenue certainty for the service providers but should be seen as a transition step from the regulated to a more competitive approach. *Service Compensation* mechanism provides to FSPs the reimbursement of 'actual incurred' costs for the provision of a system service. The costs include the start-up costs to make the resource available, generation costs to cover the cost to sustain at certain operation point, and lost opportunity cost associated with moving a resource away from its economic optimum to meet the reliability needs of the system. Such mechanism brings no cost risks to the FSP but also provides no direct incentives for the service provision. *Hybrid Tariff Compensation* combines both the regulated tariff margin and service compensation from the service provision. *Bilateral Agreement* scheme relies on individual agreements between the SO and FSPs at individually negotiated conditions. *Hybrid Tariff Competition* combines the regulated part that can cover the actual incurred costs and competitive parts that is defined by the auction with proper competition laws. *Competitive Auction* scheme assumes a procurement of flexibility through organized auction process. This scheme is prioritized by the regulation if its cost-effectiveness is sufficient, and market power exercise is prevented. The guarantee of the auction competition in the low liquidity conditions can be introduced with competition laws/regulatory oversight.

#### Contract duration and resolution

The contracts for flexibility service provision can cover a period from one day to multi-year. The resolution of these contracts can also vary from as low as dispatch time unit of a half an hour to a full day. For instance, a two-year contract with full day resolution would mean that the service is provided for 24 hours of each day within 2-year period.

### 5.3.2 Flexibility auction bidding

Auction bidding is a process of placing offers for specific flexibility products at an auction to perform flexibility service.

#### *5.3.2.1 Auction bidding rules*

Table 11 defines the parameters of auction bidding rules considered in this study. The technical rules presented for the auction bidding list major design attributes that are available in current market. They describe the means to enable higher manoeuvrability for FSPs and tools to ensure the competitive procurement results for SO. For instance, a combination of price, unit volume, and total volume caps can sustain prices at a reasonable level if prequalified capacity is sufficiently larger than the required. Such auction will accept the offers whose price value is lower than the costs of alternative service (i.e., by as diesel generators) and volume value is lower unit volume cap until the offered volume covers the total volume. Furthermore, sealed-bid auction with multiple, mutually exclusive bid can reduce the potential for the auction gaming. It is stated that such nature of the auction will make it difficult for providers to predict how their competitors will bid for a given service and will reinforce a bidding strategy that focuses on the provider’s minimum required revenue as opposed to a strategy that focuses on pricing relative to the marginal unit.

#### *5.3.2.2 Gate opening and closing times*

The timeline of the auction bidding comprises the times of MFR publication, gate opening and closing times for the energy and capacity bids, and finally the publication of selected bids as described in Table 12. First, SO submits the flexibility requirement for each product type no later than gate closure time, for each capacity or energy contracting time unit in the trading period. Then, the auction participants shall offer their capacity (or energy) volume, price, and response details (activation time, energy constrains, ramp rate) no later than gate closure time, for each contracting period in the trading period. Note that each service can be procured in an asymmetric way, with separate tenders for upward and downward flexibility reserves. The result of each auction per contracting time and per system service is communicated or otherwise published at the specified publication time.

Table 11: Parameters of auction bidding

| Attributes | Units | Description |
|---|---|---|
| **Technical rules for auction** | | |
| **Divisibility** | (Y/N) | If bid volume can be cleared partially |
| **Multi-bidding** | (Y/N) | If submission of multiple bids per contracting time is allowed. In that case the bids are mutually exclusive. |
| **Coupled symmetric bids** | (Y/N) | If acceptance of bid per an asymmetric direction can be conditioned on an acceptance of a bid for another asymmetric direction |
| **Temporal linked bids** | (Y/N) | If acceptance of bid for a time can be conditioned on an acceptance of a bid at another time. This is also referred in the literature as “parent-child” blocks. |
| **Free energy bids** | (Y/N) | If energy bids without capacity reservation are allowed |
| **Sealed-bid process** | (Y/N) | If FSPs’ bids are not revealed for public oversight |
| **Volume stacking** | (Y/N) | If simultaneous delivery of two or more services by the resource at capacity contracting time is allowed |
| **Aggregation allowed** | (Y/N) | If aggregation allowed by the bidding rules |
| **Price cap** | (Y/N) | If price cap is used for auction bidding |
| **Symmetric** | (Y/N) | If auction accepts symmetric bids |
| **Auction type** | Closed-gate<br>Continuous | Closed-gate auction has a submission deadline, called gate closure time. In continuous auction, bids are processed as soon as they are received by the market |
| **Technical rules for bids** | | |
| **Granularity** | MW | Minimum resolution of bid volume |
| **Minimum unit quantity** | MW | Minimum allowed bid volume |
| **Maximum unit quantity** | MW | Maximum allowed bid volume |
| **Availability price** | (Y/N), €/MW | Price for keeping the flexibility available for service provision |
| **Activation price** | (Y/N), €/MWh | Price for actual flexibility delivered due to the activation of service |
| **Price resolution** | €/MW | Minimum price granularity |
| **Price cap** | €/MW/h | A maximum allowable price per unit of flexibility |
| **Validity period of bids** | hours | A period when the bid offered by FSP can be activated fulfilling the product requirement |
| **Capacity contracting time units** | hours | A temporal period for which the flexibility is procured (i.e., length of the procurement blocks) |
| **Trading period** | hours | A time interval for which flexibility bids are procured |

Table 12: Timeline of market bidding

| Attribute | Units | Definition |
|---|---|---|
| **MFR Publication Time** | | A time of submission of MFR by SO for each contracting time |
| **Gate Opening Time** | Capacity<br>Energy | A gate opening time for bid submission |
| **Gate Closing Time** | Capacity<br>Energy | A gate closing time for bid submission |
| **Publication time** | Capacity<br>Energy | A time of notification of committed market positions in capacity/ energy auction |

### 5.3.3 Auction clearing

Auction clearing is a process that defines the conditions and methods for selection of winners of the auction. The attributes of auction clearing used in this study are provided in Table 13.

Table 13: Attributes of auction clearing

| Attribute | Design space | Definition |
|---|---|---|
| **Auction coupling** | Ex-ante | A relative time of auction clearing in respect to another auction |
| | Simultaneous | |
| | Ex-post | |
| **Clearing method** | Merit Order auction | A type of market clearing approach |
| | Security-constraint UC & ED | |
| | Running Program (EDM) | |
| **Price formation scheme** | Pay-as-Cleared | A scheme that defines the market pricing |
| | Pay-as-Bid | |
| | Cost-based Price | |
| | Fixed Price | |
| | VCG auction | |
| **Clearing product** | Capacity MW | A type of product that is cleared by the market |
| | Performance-adjusted MW | |
| | Scalar-adjusted MW | |
| | Effective MW | |
| **Clearing price** | Offer price | A type of bid price used to clear the market |
| | Mixed price | |
| | Performance-adjusted price | |
| **Clearing sequence** | Simultaneous | A sequential order of market clearing for asymmetric products |
| | Upward>>Downward | |
| | Downward>>Upward | |

#### Auction coupling

Auction coupling defines a relative timing of an auction clearing with another flexibility or energy auction clearing process. The possible combinations of the auction coupling include *ex-ante* and *ex-post* splitting and *simultaneous* commitment that is present in categorisation of auction coupling between the reserve and energy auction (Domínguez, 2019).

In ex-ante approach that is common in central Europe for reserve markets, TSO contracts the reserves before the clearing of the day-ahead energy market. In the ex-post, e.g., used in Ireland, the reserves are committed after the clearing of the day-ahead energy market, and TSO dispatches all providers to their market position or otherwise. In this case, TSO is following a central dispatch approach that co-optimizes the re-dispatch, the reserve procurement, and the energy balancing. Finally, the last approach that is more common to US market design assumes simultaneous co-optimization of capacity commitment to energy and reserve markets, and it is proven to be the most cost-efficient option for the system operation (Kenneth Van den Bergh, 2020).

#### Clearing method

The types of clearing methods considered for the auction design include *Merit Order auctions*, *Security-constraint Unit Commitment and Economic Dispatch (UCED)*, and *Running Program*. The merit order method orders the bids in the ascending order of their clearing price and accepts the bids until the required MFR is achieved. The security-constrained UCED follows central-dispatch paradigm. Unit commitment problem defines the generation units that shall be online (i.e., committed) at a given time, while economic dispatch optimises the operating value of these generator units to meet demand

and satisfy system reserve requirements in the most economical manner (i.e., lowest system cost) while observing reliability constraints. This method internalizes the MFR sizing problem inside the clearing process. Finally, the *Running Program* clearing is a variation of security-constraint UCED used by EDM to dispatch the diesel generators.

### Price formation scheme

Pricing formation scheme describes the methodology used to calculate the clearing price applied to the exchange of the good or service between the buyer and seller. The price formation schemes are categorized to *Pay-as-Cleared* (also known as marginal pricing or uniform-pricing), *Pay-as-Bid* (discriminatory price auction), *Fixed (regulated) Price*, *Cost-based Price*, and *Vickrey-Clarke Groves* (VCG) auction. Pay-as-Cleared clearing provides homogeneous remuneration to participants whose offers are cleared by the market. This pricing method is recommended by the European Commission for the settlement of balancing energy for standard balancing products and specific balancing products because it contributes toward a level-playing field environment among the participants, and it is more transparent for price monitoring by regulators. Overall, Paid-as-Cleared pricing can be preferrable to accommodate a market with players of heterogeneous sizes and information access and achieve more economically efficient dispatches. Paid-as-Bid can be more natural choice to remunerate heterogeneous products with different characteristics (e.g., speed of response, number of activations, start-up costs, etc.) and service price. Pay-as-Bid mechanism is more suitable in case of low liquidity or market power issues (or even regulated prices) (EU-SysFlex, 2018). Fixed Cost assumes a regulated price remuneration for service provision for all FSPs. The Cost-based Price compensated the service provision based on the incurred cost for each FSP. The VCG auction is a sealed-bid auction that is cleared in a socially optimal manner by charging each bidder the harm they cause to other bidders. This auction incentivizes bidders to report their true cost curves–as the optimal bidding strategies. For instance, the VCG auction is proposed for virtual inertia market (Poolla, 2020).

While the market-based price formation should be prioritized in all cases, it should be protected against potential exercise of market power and market gaming. If a market-based solution fails, a requirement for a mandatory service provision with cost-based remuneration can be applied.

Furthermore, the market pricing mechanisms should provide clear signals to the investors about potential market returns. This is important because the investment landscape is risky as islands do not have the economy of scale and hence are not lucrative for potential investment. For instance, marginal cost pricing may not provide sufficient certainty for investors.

### Clearing price

We consider the following clearing prices in the auction design: *Offer Price* (can be regulated price), *Mixed Price*, and *Performance-adjusted Price*. Offer Price is the price submitted by the FSP or defined by the regulation in place. Mixed Price is a single price for two products, e.g., energy and capacity or up-regulation and down-regulation capacity. Finally, *Performance-adjusted Price* is the offer price adjusted by the historical performance score of the corresponding FPU or FPG:

$$Performance - adjusted\ price\ (euro) = \frac{Offer\ Price\ \left(\frac{euro}{MW}\right)}{Historical\ Performance\ Score}$$

The performance-adjusted price gives incentive to better service provision and enables transparent performance-based clearing of the market, e.g., in the case of regulated price for system service.

### Clearing product

The clearing products considered for the auction design can be categorized to traditional *Capacity MW*, *Performance-adjusted MW*, *Scalar-adjusted MW*, and *Effective MW*.

Performance-adjusted MW comes from a concept of reliability-aware procurement (Herre, 2022). The concept argues that most reserve providers cannot guarantee 100% reliability, and the reliability of the reserve offers should be included along the volume and price to better foresee the risks for SOs and allow participation of less reliable FPUs/FPG. Here, we use *historical performance score* as a measure of FPUs/FPG reliability that is defined by its past performance. To improve the performance assessment, this score can be weighted per months with a reduction factor for older values to prioritize recent values of the performance.

The benefits of Performance-adjusted MW are in improvement of the market liquidity and encouraging superior performance for successful auction clearing. Performance-adjusted MW clearing product is calculated as follows:

$$Performace - adjusted\ MW = Offered\ MW\ \cdot Historical\ Performance\ Score$$

Scalar-adjusted MW is a clearing product defined as the offered capacity adjusted by a Product Scalar that estimates the effectiveness of a service delivery to mitigate the system technical scarcity based on FPU/FPG's capability:

$$Scalar - adjusted\ MW = Offered\ MW\ \cdot Product\ Scalar$$

Scalar-adjusted MW rewards the offered capacity MW of those FPUs/FPG that can offer greater performance than the minimum product requirement, e.g., in terms of response's full activation time. Product scalars are used by TSO in Ireland, EirGrid, to remunerate enhanced delivery of primary, secondary, and tertiary services based on the type of response (dynamic vs static) and initial trigger point of the service delivery. Other examples of Product Scalar are rewards for faster delivery times for FFR service and stacking provision of multiple balancing services, i.e., from FFR to tertiary reserve (EirGrid, 2017).

Finally, Effective MW combines the benefits of Performance-adjusted MW and Scalar-adjusted MW clearing products and estimates the effective value of the offered capacity MW based on the past performance and individual FPU/FPG's product characteristics:

$$Effective\ MW = Offered\ MW\ \cdot Historical\ Performance\ Score\ \cdot Product\ Scalar$$

For instance, Effective MW is used by regional transmission organization of Pennsylvania-New Jersey-Maryland (PJM) for Regulation A (RegA) product with fast ramp rate and Regulation D (RegD) product with slow ramp rate. In this case, Effective MW converts these products to a common unit of measure for a regulation service and enable single market clearing. The value for Product Scalar in this case is found with Marginal Rate of Technical Substitution (MRTS). The value of MRTS equal to 1 indicates that 1 MW of fast-reacting product is equivalent to 1 MW of slow-reacting product. The MRTS scalar defines isoquants, i.e., MW quantity pairs of fast and slow products that provide equal expected frequency response, that consider diminishing effectiveness of incremental MW of fast reacting RPUs.

### Clearing sequence

If the product is asymmetric, then the clearing of MFR happens in sequence, from upward to downward or vice versa. In the case of symmetric product, the upward and downward MFR are cleared simultaneously.

### 5.3.4 Auction settlement

Auction settlement is a process of financial fulfilment of contractual obligations after the assessment of the service provision according to contractual specifications of the product and product volume of FSP allocated by the auction clearing.

#### *5.3.4.1 Baseline requirements*

Baseline power is the expected (planned) output for each settlement period without service provision. The attributes of baseline requirements are given in Table 14. Baseline calculation methods can be divided into the following categories: *historical baselines* (MBMA and XofY), *declarative* or *nomination baselines* (also referred to as schedules), *calculated baselines*, *regression baselines*, and *control groups*. Furthermore, the quality of the baseline can be estimated with quality measure. Finally, the baseline gaming is verified ex-post to check that baseline changes are not correlated in any way with the changes in activation signal and shape of response to provide.

Table 14: Attributes of service baselining

| Attribute | Design space | Definition |
|---|---|---|
| **Calculation method** | MBMA | A methodology to calculate baseline |
| | X of Y | |
| | Declarative (nomination) | |
| | Regression | |
| | Calculated | |
| | Control group | |
| **Quality measure** | | A variable for baseline quality assessment |
| **Quality control** | | A requirement of baseline measurement's quality compliance |
| **Verification control** | | An ex-post verification method for potential baseline manipulation |

Calculation method

The details of the calculation methods in Table 14 are given in what follows. Meter before – meter after (MBMA) baseline methodology evaluates the delivered flexibility volume by comparing the meter readings during the period of activation ("Meter After") against average, median, maximum, or minimum value of meter readings prior to the activation ("Meter Before"). A variation of this methodology is an interpolation method. Although these methods are simple, they can provide relatively good estimation.

XofY baseline approaches calculate the baseline based on historical demand from of X days from a set of admissible days, i.e., days excluding days with previous activations and non-similar days (e.g., weekends and holidays). The variants of X of Y baseline include HighXofY, MidXofY, and LowXofY that use the maximum, average, and minimum of X days from a set of Y admissible days. Usually, the Y set consists of 5 to 10 previous days, e.g., Mid 8 of 10, High 4 of 5.

Both historical baseline methodologies MBMA and XofY can use the same day adjustment to calibrate the baseline to the measured load/generation on the day of the activation. This adjustment factor is calculated as the ratio of the actual baseline to the estimated baseline during the calibration period (3-5 hours before the flexibility activation event). The adjustment can be applied using an additive or scalar (multiplicative) approach as well as symmetrically or asymmetrically. The symmetric approach adjusts the baseline in both directions whereas the asymmetric approach only adjusts the baseline upwards (i.e., increase of the offtake/decrease of the injection) (ELIA, 2021).

The calculated baseline relies on the real-time external parameters for baseline estimation such as weather data and uses no historical data of asset offtake/injection. This methodology is commonly applied for variable RES. For instance, the baseline of wind generation can be estimated based on the measured wind speed and power curves, while the baseline for solar PV generation can be derived from solar panels characteristics (peak capacity, orientation), and measured solar irradiance and temperature.

Regression methods extend the calculated methodology to a larger set of variables, including historical injection/consumption patterns, datetime, etc. Many external variables make the approach less transparent but can provide more accurate results.

Control group methodology determines the baseline based on the average/median of measurements of the offtake/injection of customers/resources having similar characteristics but not participating in the service provision. However, such approach requires large portfolio for accurate estimation and ignores individual conditions like extreme weather events or various markets.

Declarative (nomination) baselines assume that the FSP can accurately estimate the baseline using its own methodology well in advance of real-time, hence creating binding schedules. This approach might be complex in the case of a substantial number of delivery points with high stochasticity (e.g., residential customers). Belgian TSO, Elia, proposes that a validation/prequalification of the baseline is needed before an FSP can make use of the declarative baseline methodology. Such a baseline prequalification would require that the baseline submitted by the FSP is more accurate than the default baseline methodology (High X of Y*). In addition, the FSP needs to provide a description of the method and inputs used for calculating the declarative baseline methodology. The other baseline methodologies that are related to the declarative baseline are zero baseline.

For FPUs that do not provide a MW schedule, either the MBMA (Last QH), historical (High X of Y) or a declarative baseline methodology can be chosen. A choice of baseline should be provided to the FSP but a prove of higher quality is need in comparison to the default methodology.

#### *5.3.4.2 Performance assessment*

Performance assessment is the process of quantifying and verifying the provision of a service according to the contractual specifications of the service. The attributes of the performance assessment are provided in Table 15. Two types of assessment can be applied: *continuous* and *event-based*. The continuous assessment measures the service performance over the whole period of service provision, while event-based scheme evaluates the performance only during the events when the power system experience significant technical scarcity. The types of error indicators can be categorized based on the service type to *Reference Tracking*, *Band Service*, and *Cap Service* (Bondy D. E., 2017). Reference Tracking service follows a reference signal. Band Service allows a variation of an output between an upper and lower limit. Finally, Cap Service aims to prevent the output deviation from exceeding either upper or lower bound. Finally, the performance score gives a normalized evaluation for a service provision given the allowed error tolerance.

The attributes used for financial settlement are given in Table 16. These attributes include the time resolution of the settlement, the aggregation level used to calculate the settlement, and corresponding calculation methods.

Table 15: Attributes of performance assessment

| Attribute | | Definition |
|---|---|---|
| **Assessment scheme** | Event-based | A method of performance assessment |
| | Continuous | |
| **Assessment variable** | Capacity discrepancy | A type of variable that measures the error |
| | Energy discrepancy | |
| | | |
| **Error indicator** | Reference Tracking | A type of error indicator applied to the assessment variable |
| | Band Service | |
| | Cap Service | |
| **Error tolerance** | | An allowed error level that does not deteriorate the performance score |
| **Performance score** | | A function of the error in service delivery |

Table 16: Attributes for service settlement

| Attribute | Definition |
|---|---|
| **Settlement frequency** | A temporal resolution of financial settlement calculation |
| **Aggregation level** | A level of aggregation used in settlement calculations |
| **Availability settlement** | A method for calculation of availability (capacity) payment |
| **Activation settlement** | A method for calculation of activation (energy) payment |

# 6 FLEXIBILITY MARKET DESIGN OPTIONS FOR GEOGRAPHICAL ISLANDS

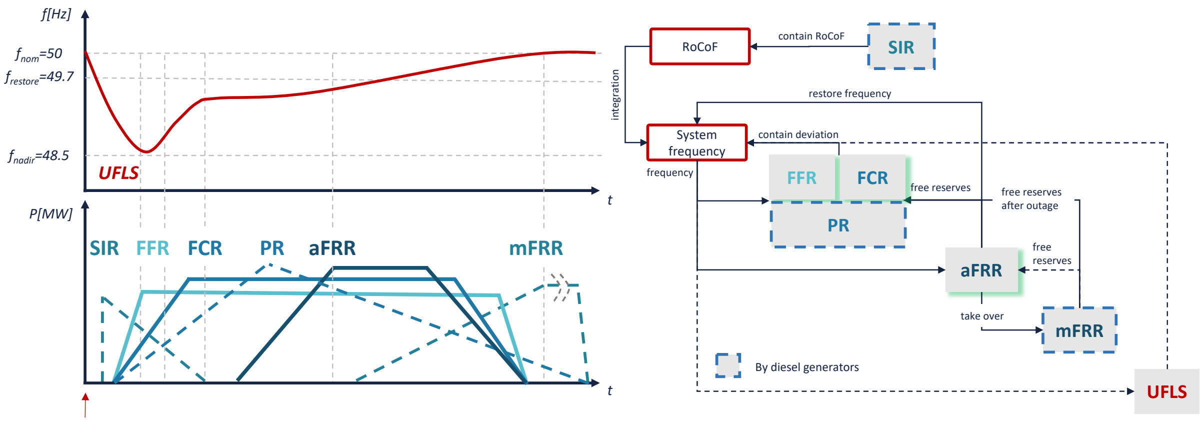
This chapter describes the proposed auction and product design for the use cases of frequency control, voltage control, and minimization of the peak consumption according to the theoretical flexibility market design framework, which was described in detail in Chapter 5.

## 6.1 FREQUENCY CONTROL

This section introduced the frequency control products and the corresponding design options for the market procurement of these products.

### 6.1.1 Product design

The load-frequency control products considered for the design consist of Fast Frequency Reserve (FFR), Frequency Containment Reserve (FCR), and automatic Frequency Restoration Reserve (aFRR) as illustrated below in Figure 8. These products aim to complement the frequency control services provided by the diesel generators, i.e., Synchronous Inertia Response (SIR), 'Primary Reserve' (PR), and mFRR. In what follows, we describe the parameters of these products.



*Loss of largest generator*

*Mayotte frequency control with new services*

**Figure 8: Schematic diagram of load-frequency control products for Mayotte island**

#### 6.1.1.1 Technical attributes

The attributes of the frequency control products are presented in Table 17 and Table 18 are discussed in what follows. These attributes of the products are inspired by the tender call for BESS by EDM, current practices for frequency control, and simulations of Mayotte power system dynamics.

**Table 17: Shape of response for frequency control products**

| Attributes | Units/Options | FFR | FCR | aFRR |
|---|---|---|---|---|
| **Allowed type of response** | Dynamic<br>Static | Dynamic | Dynamic | Dynamic |
| **Asymmetric droop rate** | % | 2 | 0.6 | n/a |
| **Dead band** | Hz (delivery %) | -0.3 (25%) | +/-0.015 (5%) | n/a |
| **Dead band step response** | (Y/N) | Yes | Yes | n/a |
| **Full delivery point** | Hz (delivery %) | 49 (100%) | 49.7/50.3 (100%) | n/a |
| **Post-fault frequency condition for recharge** | Hz | > 50.0 | > 50.0 | n/a |

Table 18: Frequency control product characteristics

| Attributes | | Units/Options | FFR | FCR | aFRR |
|---|---|---|---|---|---|
| **General characteristics** | | | | | |
| **Product type** | | | Capacity | Capacity | Capacity & Energy |
| **Location required** | | (Y/N) | No | No | No |
| **Non-tripping range** | | Hz | 46 – 55 | 46 – 55 | 46 – 55 |
| **State-of-charge management** | | Non-reserved capacity<br>Post-fault restoration | Post-fault restoration | Non-reserved capacity & post-fault restoration | n/a |
| **Aggregation allowed** | | (Y/N) | No | No | Yes |
| **Symmetric product** | | (Y/N) | Asymmetric | Symmetric | Asymmetric |
| **Asymmetric direction** | | Upward/ Downward | Upward | Upward & Downward | Upward/ Downward |
| **Timing of delivery** | | | | | |
| **Maximum preparation period** | | Seconds | n/a | n/a | 30 |
| **Maximum ramping period** | | Seconds | n/a | n/a | 250 |
| **Maximum ramping** | | MW/ seconds | n/a | n/a | n/a |
| **Max time to 50% delivery** | | Seconds | n/a | n/a | n/a |
| **Maximum full activation time** | | seconds | < 0.4 | < 1 | 300 |
| **Minimum delivery duration** | Normal Mode | minutes | 30 | Continuously | 30 |
| | Fault Mode | minutes | 30 | 30 | 20 |
| **Maximum deactivation period** | | seconds | < 0.4 | < 1 | 300 |
| **Maximum recovery period** | | hours | 12 | 12 | 0 |
| **Post-fault delay for recharge** | | Minutes | 0 | 0 | n/a |
| **Communication** | | | | | |
| **Mode of activation** | | Automatic<br>Manual | Automatic | Automatic | Automatic |
| **Activation type** | | Decentralized<br>Centralized | Decentralized | Decentralized | Centralized |
| **Activation signal** | Normal Mode | | Frequency | Frequency | FCRE |
| | Reserve Mode | (optional) | n/a | Zero-mean frequency | n/a |
| **Ramp activation signal** | | Continuous<br>Step-response | n/a | n/a | Continuous |
| **Activation scheme** | | Pro-rata<br>Merit order | n/a | n/a | Merit order |
| **Activation cycle** | | Seconds | n/a | n/a | 4 seconds |
| **Data aggregation level** | | RPU<br>RPG<br>BSP | RPG | RPU | RPU/RPG |

### Fast Frequency Reserve

Fast Frequency Reserve is a capacity product that is meant for asymmetric upward regulation in the case of contingency events to mitigate high RoCoF. In terms of comparing this product to standard European frequency control products, the FFR defined here is a mixture of upward FCR to handle disturbances (known as FCR-D) and Fast Frequency Reserve in the Nordic Synchronous Area. This product has a wide dead band from 49.7 to 50.0 Hz to prevent excessive activations within a normal operating range. Ultra-fast full activation time (FAT) of the product is provoked by the characteristics of the island system with low inertia. The precise value of 0.4 seconds was derived from the technical specifications of a previous tender for fast frequency control resources published by EDM.

The droop rate of 2% corresponds to the droop rate of symmetric conventional diesel generators for upregulation. The step response provides a rapid power injection in the case of large frequency deviations. As this product is asymmetric, a post-fault restoration is used for LER to return to maximum energy charge after a contingency event. The product has a requirement for minimum energy delivery of 30 minutes to give enough time for mFRR resources (EDM's diesel units require 10-15 minutes to start) to be activated. The FFR product could be described for RPUs providing both dynamic (continuous) and static (relay-connected step response) type of response, but the former is ignored, and its requirements are not described here because of a low volume of appropriate relay-connected RPUs on the island.

Figure 9 provides an example of quantitative analysis for MRR based on Sim7 of deliverable D2.5. In the underlying simulation, diesel generators were excluded from the frequency control. The results explain the value of FAT for the frequency stability and the choice of FAT as specified in this report. The results confirm the idea that the use of ultra-fast reacting resources decreases the overall volume required to be reserved for the support of the frequency stability. Furthermore, the comparison of the results suggests that the decrease of the system inertia significantly increases the capacity volume required to maintain frequency stability. Full activation time of 5 seconds for FCR requires too large reserve size that exceeds the current peak demand by a factor of two. The reserve requirement with only FFR product with FAT of 0.4 seconds slightly exceeds the volume of currently reserved capacity of diesel units. The use of FFR replaces the work of diesel engines in frequency control and provides cost-efficiency improvement of operational management, because it enables the usage of thermal generators in full capacity with higher efficiency and prevents extra start-up of diesel groups to maintain the required level of reserves. The aggregation of RPUs in a group is neglected because of strict FAT requirements.

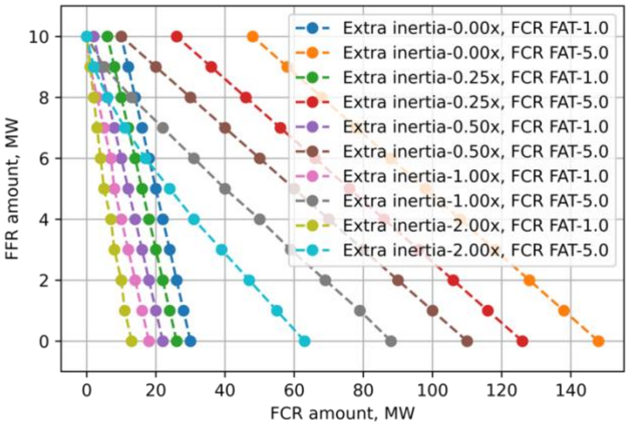


Figure 9: Minimum reserve requirement with a varying level of additional inertia

### Frequency Containment Reserve

Frequency Containment Reserve (FCR) is a capacity product that provides symmetric frequency control within normal operating range of ±0.3 Hz from the nominal value. This product assists the diesel engines in maintaining the frequency quality by mitigating rapid frequency oscillations due to low FAT of this product and high droop rate. FAT is aligned with response of diesel units considering the inertial response. The product mainly targets the inverter-based resources that can provide dynamic response, e.g., existing BESSs currently used in other applications (e.g., load shifting) in a short term, and, potentially, hydrogen electrolyzes and renewable generators in a long term. The capacity of the reserve is defined as minimum injection and withdrawn active power that the RPU can achieve within the FAT and sustain during a minimum energy delivery time. The parameters of both primary control products are shown in Figure 10.

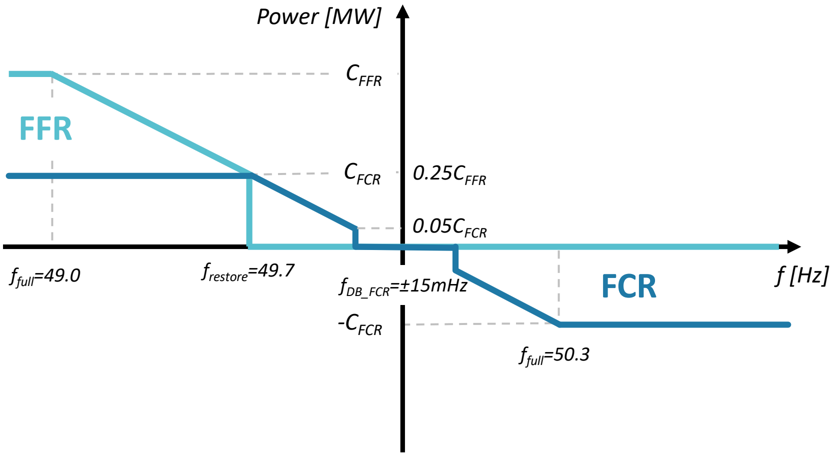


Figure 10: Droop curves of primary frequency control products

The RPUs of FCR product with LER shall have an energy reservoir sufficient to continuously activate the contracted reserve capacity in normal state or supply partial delivery for a proportionately longer period in the event of frequency deviations lower than the maximum frequency deviation and fully activate the contracted reserve capacity in the case of maximum deviation for a minimum energy delivery period (RTE, 2021). Like FFR, the product requires a minimum energy delivery of 30 minutes. In fact, this energy requirement covers the possibility of inadequate aFRR sizing and presumes that FFR and FCR cover the imbalance in the case of contingency event until mFRR is activated, while aFRR can be sized for imbalances of system net load. The power and energy capacity of LER that is not reserved for the maintaining of the reserve, may be used for active energy reservoir management but the contracted reserve capacity cannot be used for purposed other than frequency control. When an energy storage facility reaches the maximum or minimum charge level, it interrupts the activation of the reserve capacity until the direction of the balance deviation, and at the same time the direction of the activation, changes (in case of symmetric FCR). In addition, to ensure sufficient capacity for short-term frequency deviations, the LER may switch from the Normal Mode (reaction to normal frequency deviation) into a Reserve Mode (reaction to zero-mean frequency deviation), see Annex I in (RTE, 2021).

The power and energy capacity of LER that are not reserved for the maintaining of the reserve, may be used for active energy reservoir management but the contracted reserve capacity cannot be used for purposed other than frequency control. When an energy storage facility reaches the maximum or minimum charge level, it interrupts the activation of the reserve capacity until the direction of the balance deviation, and at the same time the direction of the activation, changes (in case of symmetric FCR). In addition, to ensure sufficient capacity for short-term frequency deviations, the LER providing FCR service may switch from the Normal Mode (reaction to normal frequency deviation) into a Reserve Mode (reaction to zero-mean frequency deviation), see Annex I in (RTE, 2021).

The RPUs for FFR product with LER are allowed to restore the full activation capability if the energy reservoir runs out completely after the fault event with the contracted capacity. The fault event is defined as a frequency deviation from the nominal value that exceeds the product dead band (i.e., 49.7 Hz). In the post-fault restoration, the LER unit shall operate in symmetric mode without the dead band and recharge the energy reservoir during positive frequency deviations above 50 Hz.

The stacking of the FCR and FFR products is possible either at different capacity contracting time units (CCTU) or by splitting the capacity per service as illustrated in Figure 12.

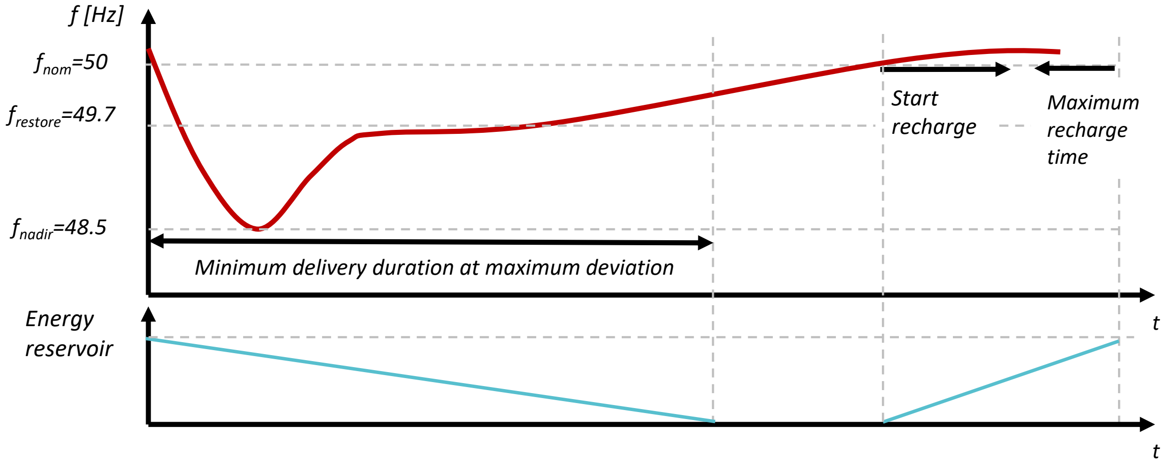


Figure 11: Post-fault energy reservoir restoration

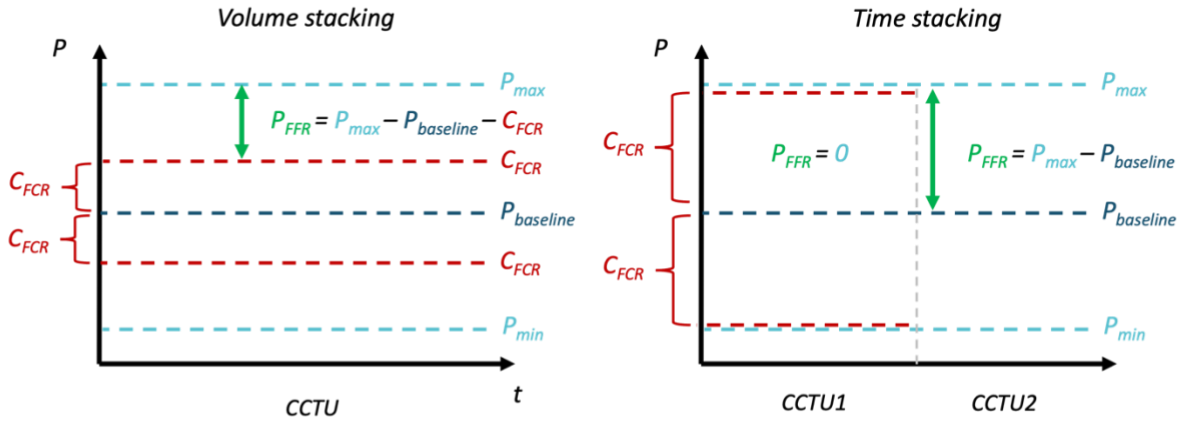


Figure 12: Stacking options for FFR and FCR products

### Automatic Frequency Reserve Restoration

The proposed product for secondary frequency control corresponds to a standard aFRR product for balancing energy and balancing capacity with a slightly modified set of characteristics. The proposed aFRR product is designed to be asymmetric to facilitate participation of those RPUs/RPGs that have no symmetric capabilities, such as solar PV installations. Moreover, the aFRR product allows aggregation to enable participation of residential and industrial VPPs in the service provision.

The timing of delivery was selected to be aligned with current harmonization of aFRR rules in Europe defined by PICASSO project. Full activation time of aFRR product is limited to 5 minutes with reparation period of 30 seconds as required by the harmonization rules. The service is activated automatically in a centralized way based on the FRCE activation signal. Ramp activation signal is continuous and prioritized over step-wise FAT signal because of higher controllability. Furthermore, merit order activation scheme is chosen, i.e., cheapest energy bids are activated first, instead of pro-rata, where the activation energy is activated proportionally among the contracted energy bids. The data exchange occurs at a frequency of 4 seconds and contains the information at the level of RPG and RPUs if needed.

#### 6.1.1.2 Prequalification

This section describes the measurement requirements, prequalification tests, and prequalification set-up for FFR, FCR, and aFRR products.

##### Measurement requirements

The minimum measurement requirements for the load-frequency control products shown in Table 19 are selected to ensure the necessary level of measurement quality necessary to control the performance conformity with the contractual obligations.

Table 19: Measurement requirements to load-frequency control products

| Parameters | | Units | FFR | FCR | aFRR |
|---|---|---|---|---|---|
| **Frequency** | | | | | |
| **Measurement error** | | mHz | ±5 | ±5 | - |
| **Resolution** | | mHz | 5 | 5 | - |
| **Sampling rate** | Monitoring | Hz | 1 | 1 | - |
| | Settlement | Hz | 10 | 10 | - |
| **Measurement availability** | | % | 98.5 | 98.5 | - |
| **Active power** | | | | | |
| **Measurement error** | | %Pmax/ MW | ±0.5%/ 0.01 | ±0.5%/ 0.01 | ±0.5%/ 0.01 |
| **Resolution** | | MW | 0.01 | 0.01 | 0.01 |
| **Sampling rate** | Monitoring | Hz (s) | 1.0 | 1.0 | 0.25 |
| | Settlement | Hz (s) | 10 | 10 | 0.50 |
| **Measurement availability** | | % | 98.5 | 98.5 | 98.5 |

##### Prequalification tests

The prequalification tests recommended for the load-frequency control products are marked in Table 20. The conformance criteria for the product prequalification include time-related technical parameters (FAT and minimum energy duration) under allowed error of activation power.

Table 20: Prequalification tests for load-frequency control products

| Power ramp test | FFR | FCR | aFRR |
|---|---|---|---|
| **Live Power Setpoint Test** | - | - | X |
| **Communication Test** | X (optional) | X (optional) | X |
| **Baseline Test** | X | X | X |
| **Step Response Test** | X | X | - |
| **Droop Response test** | X (optional) | X (optional) | - |
| **Duration Test** | X | X | X |
| **Frequency Measurement Test** | X | X | - |
| **Frequency Sweep Test** | X (optional) | X (optional) | - |
| **Live Frequency Test** | X (optional) | X (optional) | - |

##### Test setup

An example of test set-up for prequalification tests is provided in Figure 13 for decentralized (FCR/FFR products) and centralized (aFRR/mFRR products) control. For decentralized frequency control, a frequency simulator is required for the tests. The exact description of the prequalification tests, testing equipment requirements, conformance criteria will be confirmed and provided by EDM during the pilot demonstration in WP8.

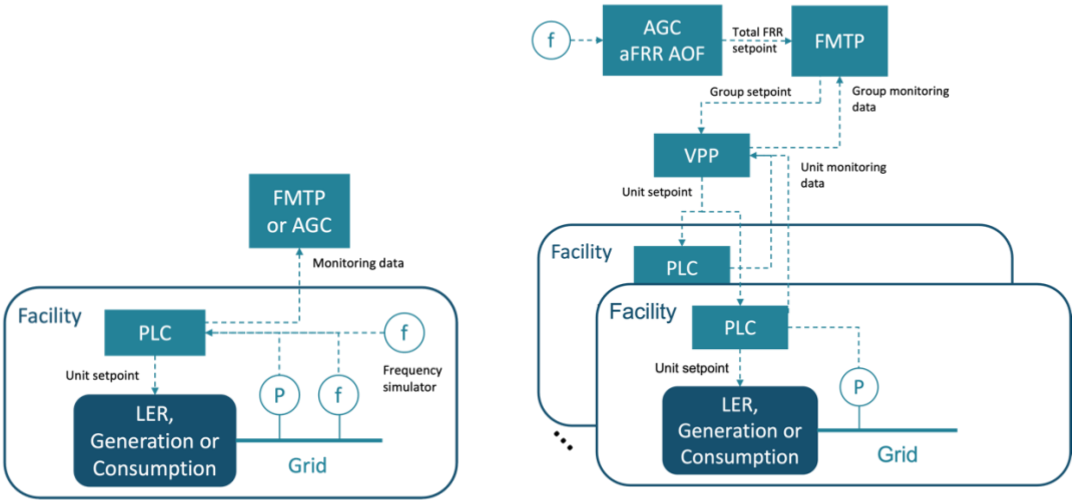


Figure 13: Prequalification test set-up for decentralized and centralized products

### 6.1.2 Auction design

This section describes the auction design of reserve market for geographical islands according to the theoretical flexibility market design framework presented in Chapter 5. Reserve sizing, reserve procurement, and reserve clearing stages are presented for three design scenarios: *EDM-BAU* that describes current SO's practices on Mayotte island, *FMTP-DEMO* shows the planned scheme that will be tested during the project pilot demonstrations, and *FMTP-FUTURE* that provides the recommended design parameters for the auction design.

#### *6.1.2.1 Flexibility procurement*

Flexibility procurement for balancing products is described with reserve sizing and reserve procurement stages.

##### Scenarios for primary control products

Table 21 and Table 22 illustrate the design scenarios for MRR sizing and procurement of FFR and FCR products.

##### EDM-BAU

Business-as-usual practices of EDM assume *static frequency sizing* of the minimum required reserves that is updated annually based on the information about new generation capacity installation, including RES. EDM uses *deterministic sizing methodology* with a reference incident of the largest diesel generator outage as a sizing variable. The sizing methodology *aims to prevent a power outage* and considers the worst case of system conditions in a representative day and uses it uniformly for all hours of the day.

The procurement of the *non-utility-owned* reserves occurs on an annual basis by organizing *voluntary competitive tenders* for long-term (> 1 year) contracts if needed. These contracts assume BSP's availability per *half-hourly daily intervals* within the contract duration.

##### FMTP-DEMO

Within the project pilot demonstrations, we aim to modify the sizing target to decrease the supply interruptions for end-users by *preventing an activation of UFLS*. For that, a *simulation-based sizing* methodology is proposed. A simulation model for Mayotte's power system dynamics is developed in T2.5 of this project and described in D2.5. This model provides the MRR to prevent UFLS with capacity of FFR and FCR products in the case of a reference incident.

The role of FMTP is to enable daily procurement of reserves. As the demonstration is limited by a few potential participants, a Service Compensation tariff is proposed for the service remuneration. The value of compensation will be defined by the BSPs based on the incurred cost of the services to the maintenance of system frequency stability. The contracts are valid for a 4 hourly block of a specific day. The 4-hour resolution is chosen to reduce the number of potential market-clearing runs. These six blocks correspond to overnight off-peak (Block 1: 00:00–04:00), morning shoulder-peak (Block 2: 04:00—08:00), morning peak (Block 3: 08:00—12:00), daytime peak (Block 4: 12:00—16:00), evening priority peak (Block 5: 16:00—20:00), and evening shoulder peak (Block 6: 20:00—00:00).

### FMTP-FUTURE

For the ideal future scenario, the preferred modifications in comparison to the previous scenarios concern shortening the sizing frequency and increasing the sizing to half-hourly intervals. This scenario recommends *a hybrid approach* for the procurement frequency that combines long-term and short-term reserve procurement. Moreover, the procurement resolution is reduced to half-hourly intervals. The competitive *auction-based procurement* should be prioritized if there is evidence suggesting the availability of a sufficient number of potential BSPs. Otherwise, more regulated Hybrid Tariff Competition can be used. Moreover, this scenario recommends using System Conditions in the MRR sizing for daily procurement as part of security-constraint UCED in combination with deterministic method used for static sizing.

Table 21: Reserve sizing for primary frequency control products FFR and FCR

| Attribute | Type | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Sizing frequency** | Static | X | X | |
| | Seasonal | | | |
| | Dynamic | | | |
| | Hybrid | | | X |
| **Sizing methodology** | Heuristic | | | |
| | Deterministic | X | | X |
| | Probabilistic | | | |
| | System Simulation | | X | |
| | System Conditions | | | X |
| **Sizing target** | Prevent power outage | X | | |
| | Prevent UFLS | | X | X |
| | Intra-period imbalance | | | |
| **Sizing variable** | Historical imbalance | | | |
| | Reference incident | X | X | X |
| | FRCE | | | |
| | Forecasted imbalance | | | |
| **Sizing convolution** | - | - | - | - |
| **Sizing resolution** | ½ hour | | | X |
| | 2 hours | | | |
| | 4 hours | | | |
| | 24 hours | X | X | |
| **Sizing reliability** | % | - | - | - |

Table 22: Reserve procurement for primary frequency control products FFR and FCR

| Attribute | Design space | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Procurement frequency** | Static | X | | |
| | Seasonal | | | |
| | Semi-dynamic | | | |
| | Dynamic | | X | |
| | Hybrid | | | X |
| **Procurement scheme** | Voluntary | X | X | X |
| | Mandatory | | | |
| **Procurement mechanism** | Competitive Auction | X | | X |
| | Bilateral Agreement | | | |
| | Regulated Tariff | | | |
| | Interconnection Condition | | | |
| | Service Compensation | | X | |
| | Hybrid Tariff Compensation | | | |
| | Hybrid Tariff Competition | | | |
| **Contract duration** | 1 day | | X | X |
| | 1 week | | | |
| | 1 month | | | |
| | 1 year | | | |
| | > 1 year | X | | X |
| **Contract resolution** | ½ hour | X | | X |
| | 2 hours | | | |
| | 4 hours | | X | |
| | 24 hours | | | |

### Scenarios for secondary control products

Table 23 and Table 24 illustrate two scenarios for MRR sizing and procurement of aFRR product: *FMTP-DEMO* and *FMTP-FUTURE*. EDM-BAU scenario is not considered because such product is not currently available for EDM.

#### FMTP-DEMO

In this scenario, the demonstration of aFRR product is conducted with the main target to reduce the intra-period imbalances based on the probabilistic analysis of historical data for planned and realized demand as well as solar PV production. In this scenario, the sizing is assumed to be static, while the procurement is realized in a dynamic way. The sizing will use the maximum of separately assessed distributions at 1% and 99% percentiles at time resolution of 2-hours blocks to get upward and downward requirements. The 2-hour blocks start at overnight off-peak (Block 1: 00:00–02:00).

The procurement of the aFRR product is organized according to the Hybrid Tariff Compensation scheme assuming that the regulated part corresponds to the capacity payment and cost-based part corresponds to the energy.

#### FMTP-FUTURE

In FMTP-FUTURE scenario, several improvements are added in equivalent way as for the primary control products. First, the sizing frequency is changed to be dynamic. Second, the probabilistic methodology of FMTP-DEMO is adjusted by relying on Graf-Haubrich approach that calculates the necessary control reserve considering convolution of independent power imbalances like power plant outages, load variations, schedule step error, and forecast error (Maurer, 2009). Finally, the procurement of the reserves is organized in a hybrid fashion with a minimum contract resolution of a half an hour.

Table 23: Reserve sizing for aFRR product

| Attribute | Type | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Sizing frequency** | Static | - | X | |
| | Seasonal | - | | |
| | Dynamic | - | | X |
| | Hybrid | - | | |
| **Sizing methodology** | Heuristic | - | | |
| | Deterministic | - | | |
| | Probabilistic | - | X | X |
| | System Simulation | - | | |
| | System Conditions | - | | |
| **Sizing target** | Prevent power outage | - | | |
| | Prevent UFLS | - | | |
| | Intra-period imbalance | - | X | X |
| **Sizing variable** | Historical imbalance | - | X | |
| | Reference incident | - | | |
| | FRCE | - | | |
| | Forecasted imbalance | - | | X |
| **Sizing convolution** | Maximum | - | X | |
| | Probabilistic | - | | X |
| **Sizing resolution** | ½ hour | - | | X |
| | 2 hours | - | X | |
| | 4 hours | - | | |
| | 24 hours | - | | |
| **Sizing reliability** | % | - | 1/99% | 1/99% |

Table 24: Reserve procurement for aFRR product

| Attribute | Type | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Procurement frequency** | Static | - | | |
| | Seasonal | - | | |
| | Semi-dynamic | - | | |
| | Dynamic | - | X | |
| | Hybrid | - | | X |
| **Procurement scheme** | Voluntary | - | X | X |
| | Mandatory | - | | |
| **Procurement mechanism** | Competitive Auction | - | | X |
| | Bilateral Agreement | - | | |
| | Regulated Tariff | - | | |
| | Interconnection Condition | - | | |
| | Service Compensation | - | | |
| | Hybrid Tariff Compensation | - | X | |
| | Hybrid Tariff Competition | - | | |
| **Contract duration** | 1 day | - | X | X |
| | 1 month | - | | |
| | > 1 year | - | | X |
| **Contract resolution** | ½ hour | - | | X |
| | 2 hours | - | X | |
| | 4 hours | - | | |
| | 24 hours | - | | |

### Scenario evaluation

Table 25 provides a qualitative comparison of the described scenarios based on the design criteria presented in section 3.4. In the following, each design criterion is discussed in detail.

Table 25: Scenario evaluation for primary and secondary control products

| Design criteria | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|
| **Operational security** | MEDIUM | MEDIUM | HIGH |
| **Cost-efficiency** | MEDIUM | MEDIUM | HIGH |
| **Regulatory compatibility** | LOW | HIGH | MEDIUM |
| **Environmental benefits** | LOW | LOW | LOW |
| **Market liquidity/competition** | LOW | MEDIUM | MEDIUM |
| **Implementation simplicity** | HIGH | MEDIUM | LOW |

### Operational security

In terms of operational security, *FMTP-DEMO* and *FMTP-FUTURE* aim to limit the frequency deviation and durations of potential supply interruptions by setting harder MRR. However, a short-term procurement in the *FMTP-DEMO* scenarios under static reserve sizing creates the risks of reserve unavailability for SO considering the low market liquidity of the reserve auction. This risk is minimized in hybrid procurement approach of *FMTP-FUTURE* scenario that combines static and dynamic procurement. It is common, that a rather large amount of the reserve needs is fixed, and only a small part varies following system conditions. In this case, the yearly procurement can be intended to cover base load variation and possible generation outage, while the daily procurement can be driven by the level of expected System Non-Synchronous Penetration and consider forecast uncertainty of renewable generation. In that case, short-term sizing of *FMTP-FUTURE* scenario can be beneficial to hedge against unforeseen critical conditions of the system state.

The reduced sizing and contract resolution in *FMTP-FUTURE* design can potentially improve the operational security in comparison to the *FMTP-DEMO* design, by providing more granular secondary reserve requirement. Furthermore, probabilistic sizing of secondary reserve with imbalances of an outage and probabilistic forecasts of renewable generation and demand can be more reliable estimation method than the historic imbalances. As the forecast errors of renewable generation can be more decisive factor for the net load imbalances, its consideration in the reserve sizing will be important.

### Cost-efficiency

The cost-efficiency of the *EDM-BAU* approach is affected by the sizing target which allows to use UFLS to decrease the risks of the generator loss. Such option is economically less costly because of lack of the corresponding cost for extra security guarantees as in the other scenarios. On the other hand, long-term reserve sizing and procurement times require the SO to consider a few rare extreme system imbalances that can increase the MRR over a longer term making it irrelevant from the technical point of view and economically stressful.

The use of Service Compensation Tariff as a procurement scheme minimizes the potential risks of uncompetitive pricing in the case of short-term procurement of *FMTP-DEMO* scenario. The shorter timeframes of the procurement in *FMTP-DEMO* scenario can allow market access for time-dependent BSPs. For instance, this approach is beneficial to those RPUs that cannot guarantee the same capacity availability level over extended period (partially weather-dependent renewables) or have time-dependent opportunity costs, e.g., responsive load or energy storage systems (Mathias Hermans, 2021).

The shorter timeframes of the reserve dimensioning and procurement in *FMTP-FUTURE* scenario can yield cost savings in the security maintenance by preventing oversizing and allow market access for time-dependent RPUs. For instance, the benefits of the short-term dimensioning and procurement in terms of the cost of balancing and reduction of the needed reserve size under the same reliability are confirmed in several studies (Mathias Hermans, 2021; De Vos, 2019; Cauwet, 2019).

#### Regulatory compatibility

Although the Commission Regulation (EU) 2017/2195 on electricity balancing is not obligatory for island power systems, the Article 32 of this directive encourages SOs to procure reserves on a short-term basis (i.e., close to delivery and with high-resolution products) to the extent possible and where economically efficient. Moreover, Article 6(9) of the Regulation on the internal market for electricity (recast), of June 2019, sets a requirement for at least 40 % of the standard balancing products to be procured no more than day-ahead, and for no longer than one day. The rest of the procurement can only be up to one month ahead if a derogation is granted by the Member State’s regulator to ensure security of supply or to improve market economy. Therefore, given the desired regulatory reference, *FMTP-DEMO* and *FMTP-FUTURE* are more compatible to the practices recommended by the regulation.

In accordance with Article 157 of the SOGL Regulation, the combination of FRR and RR reserve capacities shall be sufficient to cover and continuously respond positive or negative imbalances of the area control error for at least 99% of the time. In *FMTP-DEMO* design scenario, this requirement is fulfilled with historical net load imbalances. Furthermore, EBGL in Article 157 states that the dimensioned aFRR volume should be maximum volume of the outcomes of the deterministic approach (reference incident) or probabilistic approach. However, the use of reference incident for the aFRR sizing might hard to achieve in the context of island power systems and hence ignored from the recommendation in *FMTP-FUTURE*.

#### Market liquidity

The market liquidity is affected by procurement frequency, contract duration, and contract resolution in the scenarios of *FMTP-DEMO* and *FMTP-FUTURE*. As have been stated above, the shorter procurement time and contract duration can bring time-dependent resources to the market that cannot bind themself to long term commitments and hence improve the liquidity. However, increasing the time resolution of the contracts can also create situations where some time intervals will get higher liquidity while for the other no competition can be possible because of lack of suitable reserves. Hence, a hybrid or combined approach, as in the *FMTP-FUTURE* design, shall be prioritized because it enables short-term participation of DR, RES, and decentralized production that improve the market liquidity and it also provides the long-term predictability to SO regarding the availability of the operating reserves.

#### Environmental benefits

The choice of attributes in all the scenarios has minimal impact on the environmental benefits.

#### Implementation simplicity

From the implementation side, shorter procurement and sizing timeframes require development of automated solutions that increase the complexity of the auction. Such systems also require special knowledge for the personal to maintain the necessary infrastructure. For the base scenario *EDM-BAU*, a semi-automatic implementation is feasible where tendering and procurement are organized through telephone calls, email exchange, etc.

### 6.1.3 Auction bidding and clearing

This section describes the bidding and clearing stages of the procurement stage of balancing products in *FMTP-DEMO* design. These stages describe how offering and selection of flexibility resources shall be conducted.

#### 6.1.3.1 Auction bidding

The parameters of the auction bidding for FFR, FCR, and aFRR products are presented in Table 26. The auctions for balancing products are organized as a single-bid sealed bid process. When submitted, the bids are verified against the technical bidding rules and rejected if they violate any of the validation conditions. The divisibility in the bidding rules enables the SO to procure the capacity quantity in part or partially activate the energy bid in terms of active power or activation duration. The auctions for primary control products accept only indivisible bids, while the auctions for aFRR product allow submitting both divisible and indivisible bids to provide control flexibility to the SO if possible. The options of coupled symmetric bids and temporal linked bids are currently neglected to reduce the complexity of the auction but could be vital tools to assist BSPs in the strategy planning in future. The auction design of aFRR product allows free energy bids to enable integration of time dependent and stochastic resources for which the capacity contracting time is too long, or the capacity estimation is challenging well in advance. Regarding the volume stacking, the bidding rules follow the following principle: if RPU/RPG with limited activation capability provides several types of reserves simultaneously, the activation capability that is dimensioned and contracted for a specific product must not be used for activation in other products. The bidding rules allow the aggregation but only for aFRR products as the aggregation for primary control products is technically challenging. For all the products, a price cap can be applied if the price formation scheme assumes auction competition.

The minimum unit quantity and granularity are set to 0.1 MW to ease and widen the access to the auction for the diverse BSPs. Further decreasing these quantities might not be valuable for the system operation and monetary ineffective for BSPs. This minimum volume requirement can be seen in European reserve markets and mandated by federal rules in United States (Federal Energy Regulatory Commission, 2022). The maximum unit quantity is selected to prevent exceeding the maximum capacity of the largest generation units in Mayotte’s power system and hence deteriorate the reference incident condition. The capacity auctions are organized in 4-hour blocks for FFR and FCR and in 2-hour blocks for aFRR product that are further spitted into half-hourly periods to match the SO’s dispatch granularity. The 2-hour block of aFRR product was selected because the results of the sensitivity analysis showed that the shorter settlement periods of the downward aFRR product (one and two hours) enable larger volume of solar PV to participate in the service (by 24 for 2h case and 31% for 1h case in comparison to the 4-hour case) and hence provide more economical benefits to solar PV owners.

Table 26: Technical rules for reserve auction bidding

| Attributes | | FFR | FCR | aFRR |
|---|---|---|---|---|
| **Technical rules for auction** | | | | |
| **Divisibility** | (Y/N) | No | No | Yes |
| **Multi-bidding** | (Y/N) | No | No | No |
| **Coupled symmetric bids** | (Y/N) | n/a | n/a | No |
| **Temporal linked bids** | (Y/N) | No | No | No |
| **Free energy bids** | (Y/N) | n/a | n/a | Yes |
| **Sealed-bid process** | (Y/N) | Yes | Yes | Yes |
| **Volume stacking** | (Y/N) | Yes | Yes | Yes |
| **Aggregation allowed** | (Y/N) | No | No | Yes |
| **Price cap** | (Y/N) | Yes | Yes | Yes |
| **Technical rules for bids** | | | | |
| **Granularity** | MW | 0.1 MW | 0.1 MW | 0.1 MW |
| **Minimum unit quantity** | MW | 0.1 MW | 0.1 MW | 0.1 MW |
| **Maximum unit quantity** | MW | 10 MW | 10 MW | 10 MW |
| **Availability price** | (Y/N), €/MW | Yes | Yes | Yes |
| **Activation price** | (Y/N), €/MWh | n/a | n/a | Yes |
| **Price resolution** | €/MW | 0.01 | 0.01 | 0.01 |
| **Price cap (Y/N)** | €/MW/h | To be defined | To be defined | To be defined |
| **Validity period of bids** | hours | n/a | n/a | ½ |
| **Capacity contracting time units** | hours | 4 | 4 | 2 |

#### 6.1.3.2 Information objects

The information objects that BSPs shall submit to the market trading platform during the capacity-based and energy bidding are shown in Table 27 and Table 28.

Table 27: Bidding information for the capacity-based auctions of FFR/FCR/aFRR products

| Information | Units/ Options |
|---|---|
| **Balancing Service Provider ID** | Universal Unique Identifier |
| **Reserve Providing Group ID** | Universal Unique Identifier |
| **Reserve Providing Units ID** | Universal Unique Identifier |
| **Product Type** | FFR / FCR / aFRR |
| **Product Direction** | Upward/downward |
| **Regulation Capability** | MW |
| **Capacity Price Offer** | €/MW/h |
| **Capacity Contracting Time** | Datetime |
| **Divisibility** | (Y/N) |
| **Energy Price** | (Optional), €/MWh |

#### 6.1.3.1 Gate opening and closing times

The trading times of the frequency control products on the FMTP are presented in Table 29. The short-term reserve contracting is organized on an auction before the scheduling of generation units by the electric utility to embed the results of the clearing into the current dispatch practices of EDM.

Table 28: Bidding information for the energy-based auctions of aFRR products

| Information | Units |
|---|---|
| **Balancing Service Provider ID** | Universal Unique Identifier |
| **Reserve Providing Group ID** | Universal Unique Identifier |
| **Reserve Providing Units ID** | Universal Unique Identifier |
| **Product Type** | (FFR / FCR / aFRR) |
| **Product Direction** | (Upward/downward) |
| **Volume of the bid** | MWh |
| **Divisibility** | (Y/N) |
| **Direction of the bid** | Upward or downward |
| **Energy Price Offer** | €/MWh |
| **Validity Period** | Datetime |

Table 29: Gate opening and closing times for frequency control services

| Product | FFR+FCR | FCR | aFRR |
|---|---|---|---|
| **Direction** | Upward | Downward | Upward/Downward |
| **Trading period** | D 00—24 | D 00—24 | D 00—24 |
| **Validity periods** | - | - | 48 |
| **MRR publication** | D-1 @ 15:00 | D-1 @ 15:00 | D-1 @ 15:00 |
| **GOT* capacity (EAT)** | D-1 @ 09:00 | D-1 @ 09:00 | D-1 @ 09:00 |
| **GCT* capacity (EAT)** | D-1 @ 15:00 | D-1 @ 15:00 | D-1 @ 15:00 |
| **Publication time (EAT)*** | D-1 @ 15:30 | D-1 @ 15:30 | D-1 @ 15:30 |
| **GOT* energy (EAT)** | - | - | D-1 @ 15:30 |
| **GCT* energy (EAT)** | - | - | D @ 15 minutes before delivery time |
| **Publication time (EAT)*** | - | - | D @ delivery time |

#### *6.1.3.2 Auction clearing*

This section presents and evaluates the design scenarios for market clearing of load-frequency control products.

##### Design scenarios for primary frequency control products

Auction clearing for balancing products is presented in Table 30 for *EDM-BAU*, *FMTP-DEMO*, and *FMTP-FUTURE* design scenarios.

##### EDM-BAU

Currently, EDM procures the primary reserves simultaneously with the energy dispatch by means of Running Program that defines the dispatch schedule and reserve margin of diesel generators. Running Program relies on their merit order of diesel generators, service availability of tendered RPUs, and forecasted solar PV production for the next day. The price of the regulation per reserve margin in MW is included into the cost-based energy supply price of the utility-owned diesel generators. However, the clearing price for the BSPs procured on tenders is defined based on Pay-as-Bid scheme.

##### FMTP-DEMO

The objective of the flexibility market design for pilot demonstration is to organize the reserve procurement by accommodating two types of frequency-response products with a single market (clearing) model.

In the *FMTP-DEMO* scenario, new daily procurement of reserves is embedded into the EDM's daily dispatch in ex-ante fashion, i.e., the reserve auction clearing occurs before the energy dispatch. The clearing relies on the merit order of the clearing products and their prices. The clearing product is a Scalar-adjusted MW that define the offered Capacity MW in terms of their relative value to the system frequency stability. In the case of asymmetric products, first an upward auction is cleared and then downward.

The product scalar for primary reserve service is defined based on relative value of FAT of RPU $\boldsymbol{\tau}_i$ to the preferred response time of the FFR service $\boldsymbol{\tau}_{FFR}$:

$$Product\ Scalar\ = \frac{\boldsymbol{\tau}_{FFR}}{\max(\boldsymbol{\tau}_{FFR}, \boldsymbol{\tau}_i)}$$

For aFRR service, Capacity MW are used as clearing product. However, a scheme with Scalar-adjusted MW can also be used for aFRR if BSPs can deliver ramping time faster than the minimum requirement. The clearing price of aFRR service is defined as Mixed Price consisting of fixed-cost capacity payment and cost-based energy payment.

### FMTP-FUTURE

In the FMTP-FUTURE design, several advances are considered. First, this design recommends a use of simultaneous reserve-energy clearing with UCED. Second, the market clearing uses Effective MW and Performance-adjusted Price for the auction clearing.

Table 30: Attributes of market clearing for load-frequency control products

| Attribute | Definition | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Auction coupling** | Ex-ante | X (FFR) | X | |
| | Simultaneous | X | | X |
| | Ex-post | | | |
| **Clearing method** | Merit order auction | | X | |
| | Security-constraint UC & ED | | | X |
| | Running Program (EDM) | X | | |
| **Price formation scheme** | Pay-as-Cleared | | | X |
| | Pay-as-Bid | X (FFR) | | |
| | Cost-based Price | X | X | |
| | Fixed Price | | | |
| | VCG auction | | | |
| **Clearing product** | Capacity MW | X | X (aFRR) | |
| | Performance-adjusted MW | | | |
| | Scalar-adjusted MW | | X | |
| | Effective MW | | | X |
| **Clearing price** | Cost Price | X | X | |
| | Fixed Price | | | |
| | Offer Price | X (FFR) | | |
| | Mixed Price | | X (aFRR) | |
| | Performance-adjusted Price | | | X |
| **Clearing sequence** | Simultaneous | - | | |
| | Upward>>Downward | - | X | X |
| | Downward>>Upward | - | | |

### Scenario evaluation

The impact of proposed design options for auction clearing on the design criteria of the flexibility market framework is presented in Table 31 and discussed below.

Table 31: Impact of design options on the market design criteria

| Design criteria | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|
| **Operational security** | LOW | MEDIUM | HIGH |
| **Cost-efficiency** | MEDIUM | MEDIUM | HIGH |
| **Regulatory compatibility** | LOW | MEDIUM | LOW |
| **Environmental benefits** | LOW | LOW | LOW |
| **Market liquidity/competition** | MEDIUM | MEDIUM | HIGH |
| **Implementation simplicity** | HIGH | MEDIUM | LOW |

### Operational security

The use of Scalar-adjusted MW in *FMTP-DEMO* and Effective MW in *FMTP-FUTURE* design options supports system security by defining the actual value that a resource brings to the system. This is ignored by the current SO practices that rely on the Capacity MW based clearing products. Furthermore, the use of Performance-adjusted Price can incentivize the providers to achieve better performance in the system support. Finally, joint procurement of reserves and energy products can help to better estimate the system conditions (e.g., inertial level provided by supply generators) to clear necessary volume of frequency control reserves.

The simultaneous co-optimization can be a reasonable option to reserve sizing due to vertically integrated utility on the island. This option would leverage the efficiency of energy and reserve co-optimization in a single formulation. In the case of considering dynamics of the RPUs, this option could be beneficial for the system operation by allowing multi-reserve procurement and system-condition based service allocation.

### Cost-efficiency

*FMTP-FUTURE* design can achieve high operational cost-efficiency by joining the procurement of energy and reserves instead of separate clearing as in *FMTP-DEMO*. Such scheme allows more efficiently allocate the available resources to the energy supply and system reliability. Furthermore, if the market has enough liquidity, Pay-as-Cleared pricing scheme can contribute to savings on the reserve procurement. The use of cost-based pricing for primary control products and Mixed Price in *FMTP-DEMO* design scenario prevents the exercise of market power by BSPs.

### Environmental benefits

The design options have no significant impact on the environmental benefits.

### Regulatory compatibility

In Europe, the procurement of the reserves is separated from the energy market as it is the case for *FMTP-DEMO* design options. However, as explained above, merging of energy-reserve clearing can be particularly viable for island power systems. Furthermore, scalar-based and performance-based clearing products are not common, but the auction design uses penalties for the violation of minimum performance.

### Market liquidity/competition

The market liquidity of *FMTP-FUTURE* design scenario is supported using Effective MW in the clearing process because it gives a market access to the resources with imperfect availability and reduced capabilities. Similarly, Scalar-adjusted MW in *FMTP-DEMO* scenario encourages a participation of resources with limited product capabilities.

Implementation simplicity

In *FMTP-FUTURE* design scenario, the joint procurement adds a level of complexity to the organization of the clearing in comparison to the separated reserve and energy procurement. Furthermore, accurate monitoring of service performance adds extra requirements to the infrastructure of FMTP and BSPs.

#### 6.1.3.3 Reserve activation in real-time

For *FMTP-DEMO* design scenario, activation rules assume that platform of BSP must, at a minimum, communicate to FMTP platform at a 4-second time step basis the operation data on RPU/RPG level presented in Table 32. The management platform of BSP shall also store the data about primary/secondary frequency control per RPU stated in Table 33.

**Table 32: Monitoring data per reserve providing unit**

| Definition | Units |
|---|---|
| Date/time stamp | Datetime |
| Balancing Service Provider ID | UUID |
| Service availability per RPU/RPG | [0, 1] |
| Measured active power output | MW |
| Activated reserve power output (per product) | MW |
| Baseline power output if declarative baseline | MW |
| State of energy if LER | MWh |
| Maintained reserve capacity (upward and downward) | MW |
| Received regulation signal from SO at t-4, if aFRR | MW |
| Service correction if multiple services are provided | MW |

**Table 33: Settlement data per reserve providing unit**

| Definition | Units |
|---|---|
| Date/time stamp | Datetime |
| Input frequency, if FFR/FCR product | Hz |
| Input signal at t-4, if aFRR product | MW |
| Metered active power output | MW |
| Activated reserve power output (per product) | MW |
| State of energy if LER | MWh |
| Maintained reserve capacity (upward and downward) | MW |
| Performance baseline, which shall update any operational baseline | MW |
| Service Correction if multiple products are provided | MW |

#### 6.1.3.4 Baselining requirements

For the baseline methodology of *FMTP-DEMO* design scenario, we adopt a declarative approach (also known as "nomination baseline methodology") as a default (see Table 34). This methodology requires from the BSP to evaluate and submit the baseline shortly in advance of real time (at the latest one minute ahead for FFR/FCR products and FAT for aFRR product). This baseline is efficient for balancing products with short periods between the activation request and start of the activation to mitigate potential baseline gaming opportunities. This methodology fits well for variable loads and intermittent generation with a variable and irregular intake/offtake pattern to allow BSPs to deliver more accurate forecast. The quality of the baseline can be assessed with Quality Factor as presented in Table 34. This metric is derived from baseline quality check for aFRR product by Belgian TSO, ELIA (ELIA, 2020). Note, however, a sum of values for Baseline MW and Measurement MW at time *t* per all RPUs shall be used in case of RPG baselining. Two verification control methods can be used to assess the baseline manipulation. For primary frequency control, a frequency correlation analysis can be conducted, while for secondary control, an error-based quality assessment can be carried out.

Table 34: Baseline parameters for frequency control services

| Attribute | Value |
|---|---|
| **Calculation method** | Declarative (provider submits 1 minute/FAT ahead real time) |
| **Quality measurement** | Baseline is carried out per RPU of delivery point D<br>$Reference\ baseline(D) = \frac{1}{N}\sum_t \lvert BaselineMW(t)\rvert$<br>$Quality\ factor(D) = 1 - \frac{\sqrt{\frac{1}{N}\cdot\sum_t\left(BaselineMW(t) - MeasurementMW(t)\right)^2}}{\max(reference\ baseline, 1)}$ |
| **Quality control** | Average monthly qualitive factor >= 0.95 |
| **Verification control** | Monthly ex-post correlation analysis with frequency <5%, if FFR/FCR<br>Monthly Root Mean Square Error of baseline deviation with 2% of the outliers excluded <5%, if aFRR |

### 6.1.3.5 Flexibility settlement

The settlement between SO and BSP for the delivered frequency response and restoration services occurs with monthly frequency. The parameters of the settlement for the frequency services are presented in Table 35 and

Table 36. In all the cases, the clearing price is determined according to the scheme in Table 30. The remuneration credit rules described below are applied on a settlement period that equals to one half-hour.

Table 35: Settlement parameters for FFR/FCR service

| Attribute | Value |
|---|---|
| **Settlement Frequency** | Monthly |
| **Availability settlement** | $\sum_i^N Offered\ MW_i \cdot\ Performance\ Score_i \cdot ClearingPrice_i \cdot ProductScalar_i$ |
| **Activation settlement** | BSP follows regulated generation and consumption tariff |

For primary control products, the performance score in the settlement is defined by the accuracy of delivered system balancing in respect to the reference activation signal. The activation of primary control products is not remunerated, and BSP shall follows regulated generation and consumption tariff. However, in the case of regulated energy price, the activation settlement for the primary control products can be implemented with monthly net metering to compensate the difference between the consumption and generation tariff. In such case, the positive energy balance volume, i.e., extra energy injected to the grid over the monthly period, means a payment to the BSP by SO with a regulated energy price. Alternatively, the BSP pays a standard electricity tariff to SO for a negative energy balance over the monthly period. The aFRR activation is settled based on the bid price and delivered volume (i.e., integral of the measurement of the BSP) adjusted by the performance score. The performance is calculated as energy discrepancy between the required and delivered response. According to the clearing price scheme in Table 30 for *FMTP-DEMO* design scenario, the clearing price of aFRR product for availability payment is regulated, while the activation price is based on RPU/RPG costs for service provision.

Table 36: Settlement parameters for aFRR service

| Attribute | Value |
|---|---|
| **Settlement Frequency** | Monthly |
| **Availability settlement** | $\sum_i^N Offered\ MW_i \cdot Clearing\ Price_i$ |
| **Activation settlement** | $Performance\ Score\ (VP)\ \cdot$<br>$\sum_i^N \frac{\lvert \sum_1^{\Delta t(inseconds)/4} \text{Requested MW down}_{4s}(i) \rvert \cdot \text{Energy Clearing Price}(i)}{\Delta t(inseconds)}$<br>$Performance\ Score\ (VP)\ \cdot$<br>$\sum_i^N \frac{\sum_1^{\Delta t(inseconds)/4} \text{Requested MW up}_{4s}(t) \cdot \text{Energy Clearing Price}(i)}{\Delta t(inseconds)}$ |

### 6.1.3.6 Performance assessment

The performance assessment scheme for primary control products is illustrated in Table 37. The performance assessment aims to verify the contracted capacity has been fully employed to sustain frequency deviation. The assessment is only conducted in the case of the Frequency Event, i.e., an event of a significant frequency deviation exceeding activation threshold (EirGrid, 2019). In the case of FRR product, it can be the case of exceeding the frequency threshold at 25% of contracted capacity or full capacity activation level. The assessment is measured by the capacity discrepancy of the activated control from the contracted capacity. Cap Service error indicator is used to penalize only under-delivery of the service. The number of such assessment procedures per month can be set by a SO. The activated capacity is determined at the moment of FAT given a RPU's MW response to any Frequency Event from T - 5 to T + 60, where T is the time zero of the performance assessment. In the error formula, baseline considers capacity usage for other services, e.g., aFRR.

Table 37: Performance assessment of FFR and FCR products

| Attribute | Value |
|---|---|
| **Scheme** | Frequency event |
| **Error indicator** | Cap Service |
| **Error formula** | For upward regulation:<br>$SuppliedMW(t) = \min[Measured\ MW(t) - BaselineMW(t), 0]$<br>$MissedMW(t) = \min[Required\ MW(t) - SuppliedMW(t), 0]$<br>$DiscrepancyMW(t) = -\min[tolerance\ MW(CCTU) - Missed\ MW(t), 0]$<br>For downward regulation:<br>$SuppliedMW(t) = \max[Measured\ MW(t) - BaselineMW(t), 0]$<br>$MissedMW(t) = \max[Required\ MW(t) - SuppliedMW(t), 0]$<br>$DiscrepancyMW(t) = \max[Missed\ MW(t) - tolerance\ MW(CCTU), 0]$ |
| **Error tolerance** | $tolerance\ MW(CCTU) = \pm 5\% \cdot\ Contracted\ Capacity\ (CCTU)$ |
| **Performance score** | $Performance\ score\ (event) = 1 - \frac{\max[\lvert Capacity\ Discrepancy\ MW(t \in event) \rvert]}{Contracted\ Capacity\ MW\ (CCTU)}$ |

Frequency event-based scheme requires less infrastructure development than the continuous monitoring and enables SO to verify the service provision on demand. The assessment itself can be done manually, while the request of the locally stored measurements can be made outside the FMTP platform, e.g., by email. In future, however, a continuous monitoring of FCR service should be prioritized to achieve more accurate assessment. The examples of the continuous monitoring of service provision within the performance bounds can be found in the service terms for Dynamic Moderation, Dynamic Regulation, and Dynamic Containment balancing services procured by TSO in UK (NationalGrid, 2022).

The performance assessment scheme for aFRR product is illustrated in Table 38. The assessment is planned to be implemented continuously based on the allowed performance bounds. The error metric is an Energy Discrepancy of the reference energy activations requested by the SO. For instance, this metric is applied by Elia TSO in Belgium for evaluation of the procured aFRR service. The metric penalizes symmetrically the over- and underdeliver of activated energy bids within the specific validity period (VP).

Table 38: Performance assessment of aFRR product

| Attribute | Value |
|---|---|
| **Scheme** | Continuous monitoring |
| **Error indicator** | Performance bounds |
| **Error metric** | $Supplied\ MW\ (t) = \sum_{n=1}^{DP}\left(Baseline\ MW_n(t) - Measured\ MW_n(t) - FCR/FFR\ correction\ MW_n\ (t)\right)$<br>$DiscrepancyMW\ (t) = max[\lvert Requested\ MW(t-4) - Supplied\ MW\ (t)\rvert - \ Tolerance\ MW(VP),\ 0]$<br>$Energy\ Discrepancy\ MWh\ (VP)\ = \sum_{t\in VP}\left(\frac{Discrepancy\ MW\ (t)}{\Delta t(inseconds)}\right)$<br>$Energy\ Requested\ MWh(VP) = \sum_{t\in VP}\left(\frac{Requested\ MW(t)}{\Delta t(inseconds)}\right)$ |
| **Error tolerance** | $Tolerance\ MW(VP) = 7.5\% \cdot Energy\ Bid\ Activated\,(VP)$ |
| **Performance score** | $Performance\ score\ (VP) = 1 - \frac{Energy\ Discrepancy\ MWh\ (VP)}{Energy\ Requested\ MWh(VP)}$ |

## 6.2 PEAK DEMAND REDUCTION

This section introduces the proposed design of Peak Demand Response (Peak DR) product and the corresponding organization options for auction procurement of this product.

### 6.2.1 Product design

The trading object for Peak DR product is an Asymmetric Block Offer (ABO) illustrated in Figure 14 that models the dynamics of a resource with response and rebound blocks (O'Connell, 2015). This product is suitable for the peak demand reduction service because it can accurately describe the dynamics of wide range of resources that have temporal response-rebound dynamics or only provide the response part. For instance, it can be applied to BESSs that have discharge and charge periods analogous to response and rebound, as well as other potential demand-side resources such as air conditioning units or industrial processes with response and rebound periods.

#### *6.2.1.1 Technical conditions*

Peak DR is an energy-based product that is activated to minimize peak demand on system level of geographical island. However, the same product can be used for local DR. For that purpose, the locational information is included into the technical attributes. The product is described by ABO that consists of two asymmetric parts referred to as response and rebound.

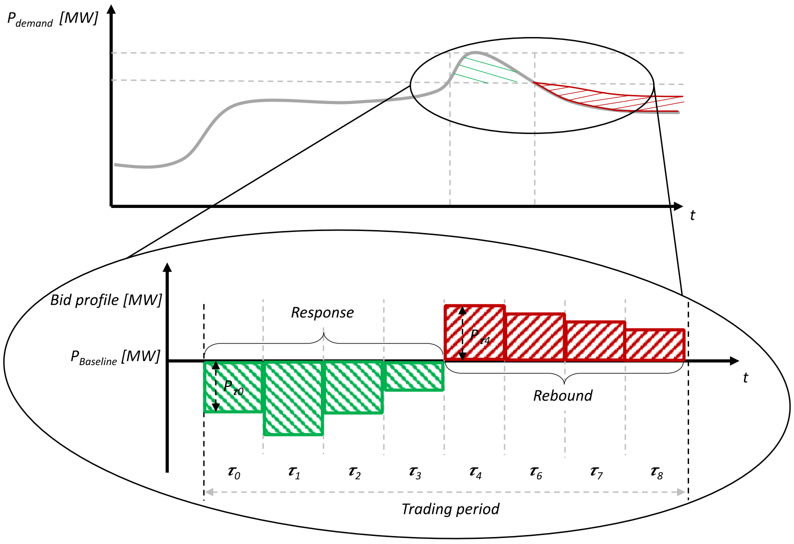


Figure 14: Example of asymmetric block offer

The response block provides an up-regulation response (i.e., load decrease or generation increase), while the rebound block models a down-regulation response (i.e., load increase or generation decrease). The block can have asymmetry in terms of the time and volume quantity. In the volume case, the rebound effect can be static (i.e., the amount of load/energy increase will be equal to the energy decrease) and dynamic (i.e., different amount of energy increase and decrease). For instance, the dynamic rebound is common to air conditioning units and BESSs operating in load shifting (or arbitrage) mode due to the losses in energy conversion process. Moreover, the flexibility of ABO definition allows to neglect a rebound part for the resources carrying out load shedding. In the time case, the profile of the ABO can vary as a function of payback length during which rebound effect is active.

In terms of time dimension, the product follows a minimum temporal resolution of half an hour. The product has no strict requirements for the maximum FAT which is set to 12.5 minutes to integrate a variety of possible resources (e.g., distributed diesel units). Furthermore, the maximum ramping rate is limited to 0.5 MW/s for fast reacting resources (e.g., battery storages) to prevent triggering of grid protection.

The product is activated automatically (remotely and locally) based on the allocated schedule, i.e., scheduled re-profiling. The monitoring of the schedule activation is carried out on a CPU or CPG level.

There is a similarity of ABO product with the capacity-based mFRR product, and hence these products could be used for similar objectives. The main difference between the two products is in the activation condition that is scheduled for the peak DR service well in advance and reserved for mFRR. To make it suitable for local congestion management, an information about the grid location is required for both products. This product can be stacked with balancing products in volume and time.

#### 6.2.1.2 Prequalification

This section describes the prequalification requirement of Peak DR product in terms of measurement requirements and organization of prequalification tests.

##### Measurement requirements

The minimum measurement requirements for Peak DR product are provided in Table 40. The sampling rate requires active power measurements and state of charge of the storage system if applicable with precision of ±10 kW (or 1% accuracy) in 5-minute steps for online monitoring and in 1-minute steps for offline settlement.

Table 39: Technical characteristics of Peak DR product

| Attributes | Units | Values |
|---|---|---|
| **General characteristics** | | |
| **Product type** | | Energy |
| **Location required** | (Y/N) | Yes |
| **Non-tripping range** | Hz | 46 – 55 Hz |
| **State-of-charge management** | (Y/N), type | n/a |
| **Aggregation allowed** | (Y/N) | Yes |
| **Symmetric product** | (Y/N) | Asymmetric |
| **Asymmetric direction** | Upward | Upward & Downward |
| | Downward | |
| **Response time attributes** | | |
| **Maximum preparation period** | Seconds | n/a |
| **Maximum ramping period** | Minutes | n/a |
| **Maximum ramping** | MW/seconds | 0.5 |
| **Maximum full activation time** | Minutes | 12.5 |
| **Minimum delivery duration** | Minutes | 5 |
| **Maximum deactivation period** | Minutes | 12.5 |
| **Maximum recovery period** | Hours | n/a |
| **Post-fault delay for recharge** | Minutes | n/a |
| **Communication** | | |
| **Mode of activation** | Automatic | Automatic |
| | Manual | |
| **Activation type** | Centralized | Centralized & decentralized |
| | Decentralized | |
| **Activation signal** | Frequency | n/a |
| | Voltage | |
| | FCRE | |
| **Ramp activation signal** | Step-response | n/a |
| | Continuous | |
| **Activation scheme** | Pro-rata | n/a |
| | Merit order | |
| **Activation cycle** | Seconds | n/a |
| **Data aggregation level** | CPU | CPU/CPG |
| | CPG | |
| | CSP | |

Table 40: Measurement requirements to Peak DR product

| Attributes | | Units | Values |
|---|---|---|---|
| **Active power** | | | |
| **Measurement error** | | %$P_{max}$/ MW | max(±1%, 0.01) |
| **Resolution** | | MW | 0.01 |
| **Sampling rate** | Monitoring | Minutes | 5 |
| | Settlement | Minutes | 1 |
| **Measurement availability** | | % | 98.5 |

### Prequalification tests

The prequalification tests for Peak DR product aim to verify the communication links, baseline quality, and minimum energy delivery. An example of test set-up for prequalification tests is provided in Figure 15. The exact description of the prequalification tests, testing equipment requirements, conformance criteria will be confirmed and provided by EDM during the pilot demonstration in WP8.

Table 41: Prequalification tests for Peak DR product

| Test | Peak DR |
|---|---|
| **Power ramp test** | - |
| **Live Power Setpoint Test** | - |
| **Communication Test** | X (optional) |
| **Baseline Test** | X |
| **Step Response Test** | X |
| **Droop Response test** | - |
| **Duration Test** | X |
| **Frequency Measurement Test** | - |
| **Frequency Sweep Test** | - |
| **Live Frequency Test** | - |

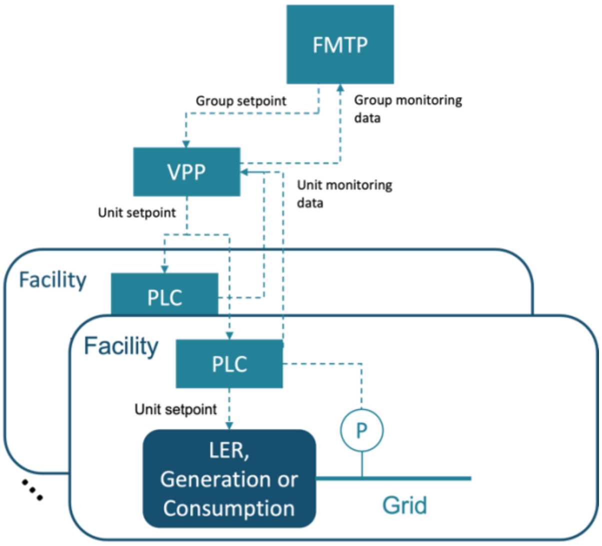


Figure 15: Prequalification test set-up for Peak DR product

### 6.2.2 Auction design

This section describes the auction design of Peak DR product for geographical islands. In what follows, this report presents the organization of the auction design according to the specifications of flexibility market design framework presented in Chapter 5. The design options of flexibility sizing, flexibility procurement, auction bidding, and auction clearing are presented for the following scenarios: *EDM-BAU* that describes current practices of system operator, *FMTP-DEMO* that shows the planned scheme that will be tested during the project pilot demonstrations, and *FMTP-FUTURE* that provides the recommended design parameters for the auction design.

#### *6.2.2.1 Flexibility procurement*

This section describes and evaluates the selected attributes for flexibility procurement of Peak DR product.

#### Scenarios for peak DR product

Table 42 and Table 43 illustrate three scenarios for sizing and procurement of MFR for Peak DR product.

### EDM-BAU

In this scenario, EDM allocates BESS for peak load shifting through tender procedure. Under business-as-usual practices of EDM, Peak DR product is statically dimensioned. The sizing is conducted deterministically using the peak-to-average ratio of the historical consumption profile of the system in the reference days. The peak demand flexibility is also procured statically for long-term contract duration (>1 year) using voluntary tenders. The contracts assume daily service provision within the contract duration with time resolution from 3 to 5 hours, depending on the representative day.

### FMTP-DEMO

The objective of this design scenario is to reduce the procurement frequency to daily frequency in comparison to *EDM-BAU* scenario. The sizing methodology addresses the KPIs of the pilot demonstrations to minimize peak demand of Mayotte power system by 15%. The exact value of MFR is estimated deterministically based on the available historical data. The procurement is organized daily and applies Regulated Tariff scheme defined based on the cost of peak power supply by diesel generators. A duration of contract is reduced to one day with a minimum resolution of ½ hour.

### FMTP-FUTURE

For the future development, a hybrid sizing and procurement can be applied. The static procurement is meant for long-term contract duration, while dynamic procurement targets short-term contract duration.  In addition, to the static sizing of *FMTP-DEMO*, the dynamic sizing methodology uses 99% percentile of probabilistic forecast of demand to estimate anticipated peak for the following day. The necessary dynamic MFR is then defined as a difference between this daily peak and average demand. Considering enough market liquidity, an attempt can be made to organize the procurement though Competitive Auction or Hybrid Competition Tariff. The MFR is obtained from a sum of static and dynamic procurement. The contract resolution of both procurement schemes corresponds to a half an hour.

Table 42: Flexibility sizing for Peak DR product

| Attribute | Type | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Sizing frequency** | Static | X | X | |
| | Seasonal | | | |
| | Dynamic | | | |
| | Hybrid | | | X |
| **Sizing methodology** | Heuristic | | | |
| | Deterministic | X | X | X |
| | Probabilistic | | | X |
| | System Simulation | | | |
| | System Conditions | | | |
| **Sizing target** | Peak demand | | X | X |
| | Peak-to-average | X | | |
| **Sizing variable** | Historical peak demand | X | X | X |
| | Forecasted peak demand | | | X |
| **Sizing convolution** | Maximum | X | X | X |
| | Probabilistic | | | |
| **Sizing resolution** | ½ hour | X | X | X |
| | 2 hours | | | |
| | 4 hours | | | |
| | 24 hours | | | |
| **Sizing reliability** | % | - | - | 99% percentile |

Table 43: Flexibility procurement for Peak DR product

| Attribute | Type | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Procurement frequency** | Static | X | | |
| | Seasonal | | | |
| | Semi-dynamic | | | |
| | Dynamic | | X | |
| | Hybrid | | | X |
| **Procurement scheme** | Voluntary | X | X | X |
| | Mandatory | | | |
| **Procurement mechanism** | Competitive Auction | X | | X |
| | Bilateral Agreement | | | |
| | Regulated Tariff | | X | |
| | Condition of Interconnection | | | |
| | Service Compensation | | | |
| | Hybrid Tariff Compensation | | | |
| **Contract duration** | 1 day | | X | X |
| | 1 month | | | |
| | > 1 year | X | | X |
| **Contract resolution** | ½ hour | | X | X |
| | 2 hours | | | |
| | > 3 hours | X | | |
| | 4 hours | | | |
| | 24 hours | | | |

### Scenario evaluation

Table 44 provides a qualitative comparison of the described scenarios based on the design criteria described in section 3.4.

Table 44: Scenario evaluation for procurement of Peak DR product

| Design criteria | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|
| **Operational security** | **MEDIUM** | **LOW** | **HIGH** |
| **Cost-efficiency** | **MEDIUM** | **MEDIUM** | **HIGH** |
| **Regulatory compatibility** | **MEDIUM** | **MEDIUM** | **HIGH** |
| **Environmental benefits** | **MEDIUM** | **MEDIUM** | **MEDIUM** |
| **Market liquidity/competition** | **LOW** | **MEDIUM** | **HIGH** |
| **Implementation simplicity** | **HIGH** | **MEDIUM** | **LOW** |

### Operational security

In *FMTP-FUTURE* design scenario, the dynamic dimensioning of MFR based on the demand forecasts in addition to the static sizing can potentially be more secure way to adequately size the necessary DR in the case of critical events. Furthermore, the hybrid procurement of the peak DR products provides more opportunities to prepare for an unexpected event closer to the real time. However, relying only on dynamic procurement as in *FMTP-DEMO* design can be risky in low liquidity conditions.

### Cost-efficiency & Market liquidity

The advantage of hybrid procurement in *FMTP-FUTURE* is in wider options for CSPs to participate in the market, and hence higher market liquidity and potential cost reduction to SO when activating these resources instead of peak diesel generators.

#### Regulatory compatibility

From a regulatory side, market-based procurement of flexibility is encouraged by the European Commission in the Directive 2019/944, Articles 32 and 61, for voltage control and congestion management, if such options are cost-effective. In this case, *FMTP-DEMO* and *FMTP-FUTURE* design options give more possibilities to participate in these markets.

#### Environmental benefits

A prevention of using peak diesel generators brings environmental value to the end-users. In all the options, the value depends on the amount of energy supply substituted by diesel generators.

#### Implementation complexity

From the point of implementation complexity, *FMTP-FUTURE* design requires the most technology and algorithm development to enable dynamic sizing and procurement that shall be integrated with daily probabilistic forecasts.

### 6.2.3 Auction bidding and clearing

The parameters of bidding rules for Peak DR auction of *FMTP-DEMO* design are provided in Table 45. The auction for peak DR product is organized as a multi-bid sealed-bid process with indivisible bids. The capacity bids of response and rebound are temporally linked, meaning that they are committed and accepted only as a whole. The bidding allows to stack the power capacity with other products if such stacking is enabled by technical capabilities of CPUs. Furthermore, the bidding supports aggregation of CPUs in CPG. However, the technical rules of bidding are also selected with possibility of acquiring small-scale CPUs and CPG of at least 0.1 MW. The maximum unit quantity is limited by the maximum capacity of large-scale generation units. The auction solely rewards the service provision with an activation price. The minimum capacity contracting time is ½ hour. The bidding validation rules shall include a price cap equal to the costs avoided by operating peak diesel generators, including their potential aging from extra start-up.

Table 45: Technical rules for Peak DR auction bidding

| Attributes | Units | Peak DR |
|---|---|---|
| **Technical rules for auction** | | |
| **Divisibility** | (Y/N) | No |
| **Multi-bidding** | (Y/N) | Yes |
| **Coupled symmetric bids** | (Y/N) | No |
| **Temporal linked bids** | (Y/N) | Yes |
| **Free energy bids** | (Y/N) | No |
| **Sealed-bid process** | (Y/N) | Yes |
| **Volume stacking** | (Y/N) | Yes |
| **Aggregation allowed** | (Y/N) | Yes |
| **Price cap** | (Y/N) | Yes |
| **Technical rules for bids** | | |
| **Granularity** | MW | 0.1 MW |
| **Minimum unit quantity** | MW | 0.1 MW |
| **Maximum unit quantity** | MW | 10 MW |
| **Availability price** | (Y/N), €/MW | No |
| **Activation price** | (Y/N), €/MWh | Yes |
| **Price resolution** | €/MW | 0.01 |
| **Price cap (Y/N)** | €/MW/h | To be defined |
| **Validity period** | hours | n/a |
| **Capacity contracting time units** | hours | ½ |

#### 6.2.3.1 *Information objects*

For the auction of Peak DR product, the information object shall contain the data described in Table 46. In the information object, the CSP should describe the profile of the ABO within the contracting period of Peak DR product with a set of capacity bids that should be activated. The capacity bids would include the upwards and downward bids that correspond to response and rebound parts of the ABO profile. The power deviations from baseline caused by DR activation but situated outside the contracting period of peak DR auction are ignored.

Table 46: Bidding information for the energy-based auctions of Peak DR products

| Energy auction | Units |
|---|---|
| **Capacity Service Provider ID** | UUID |
| **Capacity Providing Group ID** | UUID |
| **Capacity Providing Units ID** | UUID |
| **Product Type** | Peak DR |
| **Product Direction** | Upward/downward |
| **Regulation Capability** | MW |
| **Capacity Price Offer** | €/MW/h |
| **Capacity Contracting Time** | Datetime |
| **Baseline Power** | MW |
| **Point of Delivery Area** | Customer connection point |

#### 6.2.3.2 *Gate opening and closing times*

The timing requirements of the Peak DR auction bidding are illustrated in Table 47. The bidding process for day D starts at gate opening time (GOT) of 9 a.m. of day D-1 and closes at gate closing time

(GCT) of 4 p.m. of day D-1 to incorporate the results of auction clearing into the dispatch program of EDM.

Table 47: Gate opening and closing times for Peak DR auction

| **Product** | **Peak DR** |
|---|---|
| **Direction** | Upward/Downward |
| **Trading period** | D 18—22 |
| **Capacity Contracting Periods** | 1—8 |
| **MFR publication** | D-1 @ 09:00 |
| **GOT* capacity (EAT)** | D-1 @ 09:00 |
| **GCT* capacity (EAT)** | D-1 @ 16:00 |
| **Publication time (EAT)*** | D-1 @ 16:30 |

### 6.2.3.3 Auction clearing

The aim of day-ahead capacity auction is to enable the market-based integration of BESSs, EV charging stations, and potentially local energy communities while minimizing the financial and environmental costs of peak operation currently provided by diesel generators and BESSs. This section describes the auction clearing design options for peak DR product.

#### Scenarios for peak DR product

For the auction clearing, several scenarios are considered that are divided into *EDM-BAU*, *FMTP-DEMO*, and *FMTP-FUTURE*.

#### EDM-BAU

The auction clearing in the current approach happens based on a fixed schedule of peak demand reduction that is aligned with dispatch by Running Program. The schedule is obtained for representative days of weekdays, weekends, and holidays. The pricing of the clearing is defined by the Offer Price method of the tendering procedure. The clearing product is Capacity MW linked to ABO with response and rebound times.

#### FMTP-DEMO

In this design option, it is proposed to organize an ex-ante *day-ahead DR auction* with merit order clearing. The clearing product is a DR capacity volume of the ABO within the contracting time $\mathcal{T}$:

$$Capacity\ MW\ (MW) = \sum_{t\in\mathcal{T}}^{N} P_t^{\mathrm{ABO},\,response}$$

The clearing price is determined as a Mixed Price of response and rebound blocks of ABO. This price is calculated as relative cost improvement of using offered ABO in the peak reduction in comparison to the typical usage of the peak diesel generators. To achieve the project's KPIs of 10% cost reduction in peak demand supply, the reward price of the response part is rewarded at the price equal to 90% of the price of peak diesel generators. Therefore, the response part of the offered ABO should be at least 1.1 times larger than the rebound to have a positive cost-effective impact on the system peak demand reduction.

$$Mixed\ Price\left(\frac{€}{MW}\right) = \sum_{t\in\mathcal{T}}^{N} \underbrace{P_t^{ABO,\,response}\cdot 0.9\pi_t^{diesel}}_{ABO_{benefit}} - \underbrace{P_t^{ABO,\,rebound}\cdot \pi_t^{diesel}}_{ABO_{cost}}$$

The bids are cleared based on the merit order of Mixed Price and Capacity MW.

#### FMTP-FUTURE

In this design option, the *day-ahead multi-bid DR auction* with *price-as-bid* pricing scheme is organized along the economic dispatch. The economic dispatch aims to minimize the costs of energy supply with Capacity MW linked to ABO as clearing products. In this case, the extra costs of rebound and cost reduction of DR are explicitly considered along the costs of other generation units. Furthermore, Performance-adjusted Price can be used to motivate the CSPs to estimate the available DR capacity more accurately. An example of such market clearing can be found in the literature (Kok, Kazempour, & Pinson, 2020).

Table 48 Design scenarios for auction clearing of Peak DR product

| Attribute | Definition | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Market coupling** | Ex-ante | | X | |
| | Simultaneous | X | | X |
| | Ex-post | | | |
| **Clearing method** | Merit order auction | | X | |
| | Security-constraint UC & ED | | | X |
| | Running Program (EDM) | X | | |
| **Price formation scheme** | Pay-as-Cleared | X | | X |
| | Pay-as-Bid | | | |
| | Cost-based Price | | | |
| | Fixed Price | | X | |
| | VCG auction | | | |
| **Clearing product** | Capacity MW | X | X | X |
| | Performance-adjusted MW | | | |
| | Scalar-adjusted MW | | | |
| | Effective MW | | | |
| **Clearing price** | Cost price | | | |
| | Fixed price | | | |
| | Offer price | X | | |
| | Mixed price | | X | |
| | Performance-adjusted price | | | X |
| **Clearing sequence** | Simultaneous | X | X | X |
| | Upward>>Downward | | | |
| | Downward>>Upward | | | |

#### Scenario evaluation

The comparison of the design options based on the design criteria is presented in Table 49.

Table 49: Impact of design options on the market design criteria of Peak DR products

| Design criteria | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|
| **Operational security** | MEDIUM | LOW | HIGH |
| **Cost-efficiency** | MEDIUM | MEDIUM | HIGH |
| **Regulatory compatibility** | MEDIUM | MEDIUM | MEDIUM |
| **Environmental benefits** | HIGH | LOW | HIGH |
| **Market liquidity/competition** | LOW | MEDIUM | HIGH |
| **Implementation simplicity** | HIGH | MEDIUM | LOW |

#### Operational security

The clearing method of fixed schedules with representative days applied in *EDM-BAU* scenario might lack some optimality of schedule allocation considering day-to-day load variation. The clearing solution of *FMTP-DEMO* design relies on a total benefit that the ABO provides within the contracting period. Such clearing considers no possibilities of temporal matching of the response/rebound activations within the contracting period. In this case, the rebound part of ABO bids might coincide and cause even a bigger peak demand. Such approach is then not optimal from the point of operational security as it might eventually lead to a start-up of diesel generators. In this case, the day-ahead economic dispatch of *FMTP-FUTURE* is a priority option because it allows to foresee the drift of the peak demand in short-term and activate the bids correspondingly.

#### Cost-efficiency

The cost-efficiency of *EDM-BAU* scenario can be high if the tender is competitive, and there is small seasonal variation of demand that makes the representative days a valid option for schedule allocation. *FMTP-DEMO* design can potentially be cost-ineffective if temporal coincidence of rebound bids results into extra start-up of peak diesel generators. Finally, the approach in *FMTP-FUTURE* scenario is seen to be the most cost-effective as it explicitly considers the system condition and costs of DR capacity bids.

#### Regulatory compatibility

No significant impact of the design decisions on the regulatory compatibility has been identified in the presented auction clearing scenarios.

#### Environmental benefits

In terms of environmental impact, all design options are beneficial because they replace low efficient peak diesel generators. The environmental impact in *EDM-BAU* design is medium because it is dimensioned to prevent the start-up of the peak diesel units but misses daily load variation. The impact in *FMTP-DEMO* scenario is low because of the potential temporal coincidence explained above. Finally, the effect in *FMTP-FUTURE* scenario is high as it explicitly considers the dispatch of diesel units.

#### Market liquidity

Market liquidity is low for *EDM-BAU* design because it prioritizes the long-term commitment and availability of flexibility that are not suited for many CSPs. In this case, two other scenarios are more beneficial to the market liquidity because they can integrate resources with small temporal availability and, in the case of *FMTP-FUTURE* scenario, long-term CSPs.

#### Implementation simplicity

From the implementation side, *FMTP-FUTURE* design scenario requires the most amount of the resources as it necessitates to replace the legacy economic dispatch and integrate it with the peak DR auction. *FMTP-DEMO* design also requires the FMTP development in daily operation cycle, but the algorithmic part is more trivial than in *FMTP-FUTURE* design scenario.

### *6.2.3.4 Flexibility activation in real-time*

The monitoring and settlement data for Peak DR product is provided in Table 50 and Table 51.

Table 50: Monitoring data per CPU of Peak DR product

| Attribute | Units |
|---|---|
| Date/time stamp | Datetime |
| Capacity Service Provider ID | UUID |
| Service Availability per CPU/CPG | Boolean |
| Measured Active Power Output | MW |
| Activated Power Output (per product) | MW |
| Baseline Power Output if declarative baseline | MW |
| State of Energy if LER | MWh |
| Service Correction, if other service is provided by the units | MW |

Table 51: Settlement data per CPU of Peak DR product

| Attribute | Units |
|---|---|
| Date/time stamp | Datetime |
| Metered Active Power Output | MW |
| Activated Power Output (per product) | MW |
| State of Energy, if LER | MWh |
| Performance Baseline, which shall update any operational baseline | MW |
| Service Correction, if other service is provided by the units | MW |

### 6.2.3.5 Baselining requirements

A declarative approach (also known as "nomination baseline methodology") is adopted here as a default v approach in *FMTP-DEMO* design scenario. This methodology fits into the energy management of CSPs with BESSs and EVs. The baseline is assessed on the level of CPG in the case of aggregation. If the default methodology is not suitable for CSP, an alternative approach can be offered if the efficiency of this approach is proven its better quality. For instance, meter before – meter after (MBMA) methodology can be suitable for CSPs with aggregated load. The baseline parameters of declarative approach correspond to Table 34 for frequency control products.

### 6.2.3.6 Auction settlement

The settlement mechanism of Peak DR product remunerates the CSPs for the peak capacity activation in EUR/MWh as described in Table 52. Note that CSPs follow regulated consumption tariff for the rebound and baseline part.

Table 52: Settlement attributes for Peak DR product

| Attribute | Value |
|---|---|
| **Settlement Frequency** | Monthly |
| **Availability settlement** | n/a |
| **Activation settlement** | $\sum_{t\in\mathcal{T}}^{N} Capacity\ MW_i(t) \cdot\ Performance\ Score_i \cdot Clearing\ Price_i \cdot Capacity\ Contracting\ Time\ Unit(in\ hours)$ |

### 6.2.3.7 Performance assessment

The performance of the demand reduction is measured using Energy Discrepancy between the scheduled active power activation with the contracted capacity and the actual metered energy reduction per each validity period. Performance Bounds error indicator is applied with a tolerance band in the capacity activation. The attributes of the performance assessment for *FMTP-DEMO* design scenario are presented in Table 53.

Table 53: Performance assessment of Peak DR product

| Attribute | Value |
|---|---|
| **Scheme** | Continuous monitoring |
| **Error indicator** | Performance bounds |
| **Error metric** | $Supplied\ MW\ (t) = \sum_{n=1}^{DP}\left(Baseline\ MW_n(t) - Measured\ MW_n(t) - Service\ correction\ MW_n\ (t)\right)$<br>$Supplied\ MWh\ (CCTU)\ = \frac{1}{2}\sum_{t \in VP}\left(SuppliedMW\ (t) - SuppliedMW\ (t - 1)\right) \cdot \Delta t(inseconds)$<br>$Energy\ Discrepancy\ MWh\ (CCTU) = \max[\lvert Scheduled\ MWh(CCTU) - SuppliedMWh\ (CCTU)\rvert - \ tolerance\ MWh(CCTU),\ 0]$<br>$Energy\ ScheduledMWh\ (CCTU) = \sum_{t \in VP} Scheduled\ MW(t) \cdot \Delta t(inseconds)$ |
| **Error tolerance** | $tolerance\ MWh(VP) = 10\% \cdot Energy\ Scheduled\ MWh(CCTU)$ |
| **Performance score** | *Performance score (VP) = 1 --* $\frac{Energy\ Discrepancy\ MWh\ (CCTU)}{Energy\ Scheduled\ MWh\ (CCTU)}$ |

## 6.3 VOLTAGE CONTROL

This section introduces the voltage control product and the corresponding auction design according to the flexibility market design framework in Chapter 5.

### 6.3.1 Product design

The voltage-reactive power (Volt-VAR) control product with static voltage control droop curves is selected as a voltage control product. In voltage-reactive power mode, VPUs shall control its reactive power output as a function of voltage following a voltage-reactive power piecewise linear characteristic. Voltage Providing Units need to absorb a reactive power in the event of voltage rise and inject the reactive power in the event of voltage decrease. This product primarily targets such VPUs as medium-scale and large-scale solar PV plants that are distributed on the Mayotte island and other geographical islands.

In Europe, technical standard EN 50549-1 (CENELEC, 2015) and EN 50549-2 (CENELEC, 2015) describe the technical specifications of voltage control for the generators of type A and B connected to LV and MV networks. Furthermore, the network code “Requirements for Generators” states the requirements for categories B, C and D generators above 1 MW in the synchronous areas of Continental Europe. Finally, IEEE 1547-2018 standard (IEEE, 2018) establishes criteria and requirements for interconnection of DERs with electric power systems, including Volt-VAR control.

The droop response can be asymmetric, with different reactive power and voltage set points. According to the technical standard, reactive power setpoint and excitation shall be in the range from 0 to 48 % of stated apparent power. The parameters of the Volt-VAR droop curve are location-specific and depend on the characteristics of the distribution system and utility operational objectives. Therefore, the exact parameters of the product are not presented here but will be defined in WP8 when the exact VSPs and locations are known.

The dynamics of the reactive power response to a voltage change is described by a first-order transfer function with a time constant configurable in the range of 3 s to 60 s. This constant predetermines the timing of the response to be within 10—180 seconds for reaching full reactive power response with a maximum tolerance ±5% plus a time delay of up to 3 seconds deviating from an ideal first order filter response.

The activation mode of the Volt-VAR product assumes decentralized automatic activation based on the local voltage measurements. If needed, the measurements of activated reactive power and voltage are presented to the SO per a specific VPU.

Table 54: Technical characteristics of Volt-VAR product

| Attributes | Units | Volt-VAR |
|---|---|---|
| | **General characteristics** | |
| **Product type** | | Capacity |
| **Location required** | (Y/N) | Yes |
| **Non-tripping range** | Hz | 46 – 55 Hz |
| **State-of-charge management** | (Y/N), type | n/a |
| **Aggregation allowed** | (Y/N) | n/a |
| **Symmetric product** | (Y/N) | Asymmetric |
| **Asymmetric direction** | Type | Upward/Downward |
| | **Response time attributes** | |
| **Maximum preparation period** | Seconds | n/a |
| **Maximum ramping period** | Seconds | n/a |
| **Maximum full activation time** | Seconds | 10—180 seconds |
| **Minimum delivery duration** | Minutes | Continuous |
| **Maximum deactivation period** | Seconds | n/a |
| **Maximum recovery period** | Hours | n/a |
| **Post-fault delay for recharge** | Minutes | n/a |
| | **Communication** | |
| **Mode of activation** | Automatic<br>Manual | Automatic |
| **Activation type** | Centralized<br>Decentralized | Decentralized |
| **Activation signal** | Frequency<br>Voltage<br>FCRE | Voltage |
| **Ramp activation signal** | Step-response<br>Continuous | n/a |
| **Activation scheme** | Pro-rata<br>Merit order | n/a |
| **Activation cycle** | Seconds | n/a |
| **Data aggregation level** | VPU<br>VPG<br>VSP | VPU/VPG |

#### *6.3.1.1 Technical conditions*

The example characteristics of Volt-VAR control curve are illustrated in Figure 16, and the ranges for the parameters derived from IEEE 1547-2018 standard are shown in Table 55.

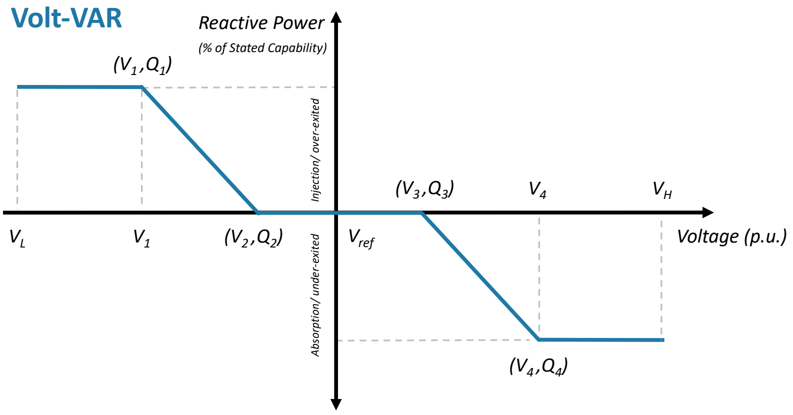


Figure 16: Voltage-reactive power droop characteristic

Table 55: Voltage-reactive power settings for normal operating performance

| Parameter | Minimum | Maximum |
|---|---|---|
| $\boldsymbol{V_{Ref}}$ | $0.95V_N$ | $1.05V_N$ |
| $\boldsymbol{V_2}$ | $V_{Ref} - 0.03V_N$ | $V_{Ref}$ |
| $\boldsymbol{Q_2}$ | $Q_N$, absorbtion | $Q_N$, injection |
| $\boldsymbol{V_3}$ | $V_{Ref}$ | $V_{Ref} + 0.03V_N$ |
| $\boldsymbol{Q_3}$ | $Q_N$, absorbtion | $Q_N$, injection |
| $\boldsymbol{V_1}$ | $V_{Ref} - 0.18V_N$ | $V_2 - 0.02V_N$ |
| $\boldsymbol{Q_1}$ | 0 | $Q_N$, injection |
| $\boldsymbol{V_4}$ | $V_3 + 0.02V_N$ | $V_{Ref} + 0.18V_N$ |
| $\boldsymbol{Q_4}$ | $Q_N$, absorption | 0 |

#### 6.3.1.2 Prequalification

This section describes the prequalification requirement of Volt-VAR product in terms of measurement requirements and lists required prequalification tests.

##### Measurement requirements

The requirements to the voltage and reactive power measurements are derived from IEEE 1547-2018 standard and presented in Table 56. The service is provided continuously within the contractual period after the prequalification tests are passed. The product carries out an automatic control of injected or absorbed reactive power in response to a locally voltage. The control signal is obtained by pre-processing the raw voltage amplitude measurements of measurement window with square root of mean squares formula.

##### Prequalification testing

The prequalification testing of the Volt-VAR control product includes a voltage step test and communication testing. In the step response test, the voltage is increasing from 0.91 p.u. to 1.1 p.u. in steps of 0.01 p.u. with the time delay at each step equal two times the FAT to obtain a steady-state value. The test set-up for the voltage tests is illustrated in Figure 17.

Table 56: Minimum measurement and calculation accuracy requirements

| Parameter | Units | Value |
|---|---|---|
| | **Voltage** | |
| **Measurement accuracy** | % of nominal voltage, $VN$ | ±1% |
| **Measurement window** | cycles | 10 |
| **Measurement range** | p.u. | 0.2 – 1.0 |
| **Measurement sampling rate** | seconds | 1 |
| | **Reactive power** | |
| **Measurement accuracy** | % of apparent power, $SN$ | ±5% |
| **Measurement window** | cycles | 10 |
| **Measurement range** | p.u. | 0.2 – 1.0 |
| **Measurement sampling rate** | seconds | 1 |
| **Measurement availability** | % | 98.5 |

Table 57: Prequalification tests for peak Volt-VAR product

| Power ramp test | Volt-VAR |
|---|---|
| **Live Power Setpoint Test** | - |
| **Communication Test** | X (optional) |
| **Baseline Test** | - |
| **Step Response Test** | X |
| **Droop Response test** | - |
| **Duration Test** | - |
| **Frequency Measurement Test** | - |
| **Frequency Sweep Test** | - |
| **Live Frequency Test** | - |

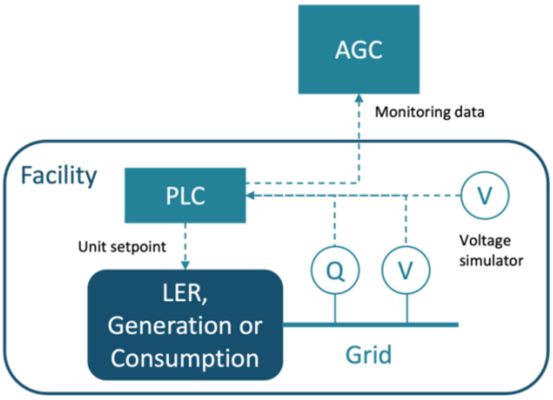


Figure 17: Prequalification test set-up for Volt-VAR product

### 6.3.2 Auction design

This section describes the design options of flexibility procurement stage of voltage control auction according to the flexibility market design framework presented in Chapter 5. Note that the details of auction bidding and clearing, including technical bidding rules, auction clearing, and auction settlement for Volt-VAR product, are not described here because will be defined by EDM in specific bilateral agreements.

#### 6.3.2.1 Flexibility procurement

This section presents the design of *EDM-BAU*, *FMTP-DEMO*, and *FMTP-FUTURE* design scenarios in Table 58. Importantly, although this use case is not organized through FMTP platform, we keep the naming conventions for design options as in the previous use cases to divide between current practices, demo tests, and future suggestions. The sizing of the flexibility is neglected in all the scenarios because it is defined by the parameters of VPUs.

EDM-BAU

In this design option, we describe the present usage of EDM's thermal power plants for voltage control. The procurement frequency can be considered dynamic as it depends on the results of economic dispatch of diesel generators. The dispatch generators are obliged to provide the service under the connection agreement.  These conditions remain in force during the lifetime of the providing unit. The minimum resolution of the contract corresponds to the minimum dispatch period of half an hour.

FMTP-DEMO

During the pilot demonstrations, a semi-dynamic procurement will be organized with the VSP under voluntary procurement scheme described by a bilateral agreement. The duration of the contract is one month with half-hourly contract resolution. Note that the contract parameters can be corrected by the EDM in the later stage of the project.

FMTP-FUTURE

This design option recommends establishing mandatory provision of Volt-VAR control for new installations as the network condition for interconnection.  Therefore, the contract is discretised per dispatch resolution and remains valid while the connection condition is preserved.

Table 58: Flexibility procurement for Volt-VAR product

| Attribute | Type | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|---|
| **Procurement frequency** | Static (yearly) | | | X |
| | Seasonal | | | |
| | Semi-dynamic | | X | |
| | Dynamic | X | | |
| | Hybrid | | | |
| **Procurement scheme** | Voluntary | | X | |
| | Mandatory | X | | X |
| **Procurement mechanism** | Competitive Auction | | | |
| | Bilateral Agreement | | X | |
| | Regulated Tariff | | | |
| | Interconnection Condition | X | | X |
| | Service Compensation | | | |
| | Hybrid Tariff Compensation | | | |
| **Contract duration** | 1 day | | | |
| | 1 month | | X | |
| | 1 year | | | |
| | > 1 year | X | | X |
| **Contract resolution** | ½ hour | X | X | X |
| | 2 hours | | | |
| | 4 hours | | | |
| | 24 hours | | | |

### Scenario evaluation

The design scenarios for flexibility procurement of Volt-VAR product are evaluated according to the design criteria in Table 59.

Table 59: Scenario evaluation for procurement of Volt-VAR product

| Design criteria | EDM-BAU | FMTP-DEMO | FMTP-FUTURE |
|---|---|---|---|
| **Operational security** | HIGH | LOW | HIGH |
| **Cost-efficiency** | HIGH | MEDIUM | HIGH |
| **Regulatory compatibility** | HIGH | HIGH | HIGH |
| **Environmental benefits** | LOW | LOW | LOW |
| **Market liquidity/competition** | LOW | LOW | LOW |
| **Implementation simplicity** | HIGH | MEDIUM | HIGH |

### Operational security

The operational security of the design options is estimated higher for mandatory provision of voltage control by VPUs, i.e., *EDM-BAU* and *FMTP-FUTURE*, as this option potentially can engage more resources in the voltage control.

### Cost-efficiency

From the cost-efficiency perspective, the locational dependency of the product leads to an extremely low liquidity condition, in which the competition of the auction-based procurement schemes is not guaranteed. In this case, including mandatory voltage control into the Interconnection Condition presumes that the costs of this service are covered by the energy prices for generators. This scheme has no extra costs for the SO and its positive impact on the cost-efficiency is higher than in the other schemes. Bilateral agreements or regulated tariffs can be applied to the existing installations where technical scarcities of voltage quality have been identified, but these schemes will have the corresponding costs.

### Regulatory compatibility

From a regulatory side, the bilateral agreements or mandatory service provision through grid code requirements are the default solution in Europe (ELIA, 2018). In fact, in many European countries, the running generators are obliged to provide voltage regulation services to TSO. Voltage related services are usually defined within the grid codes due to the local nature of reactive power. In case of an additional provision, regulated prices are used.

### Environmental benefits

No significant impact on the environmental benefits has been foreseen in all the scenarios.

### Implementation complexity

From the practical perspective, carrying out bilateral agreements is more resource-demanding that establishing single condition of interconnection. The implementation efforts can outweigh potentially low monetary value of the service.

# 7 INNOVATION POTENTIAL OF FLEXIBILITY MARKETS FOR GEOGRAPHICAL ISLANDS

This chapter explains the innovation potential that can be applied to the organization of flexibility markets on geographical islands. The chapter starts with introduction of methods to product specifications and their compatibility with the context of geographical islands. Then, an example of market restructuring to achieve the suggested product specification is shown.

## 7.1 PRODUCT SPECIFICATION

The existing approaches to the flexibility product design standardization could be divided based on the product specification, as illustrated by Figure 18. In (EU-SysFlex, 2018), these approaches are categorized to *'superproduct'* and *'supermarket'* extremes, in between of which there is a current market approach that is commonly used by SOs to procure flexibility services. In what follows, we examine these categories and analyze their compatibility with conditions of geographical islands.

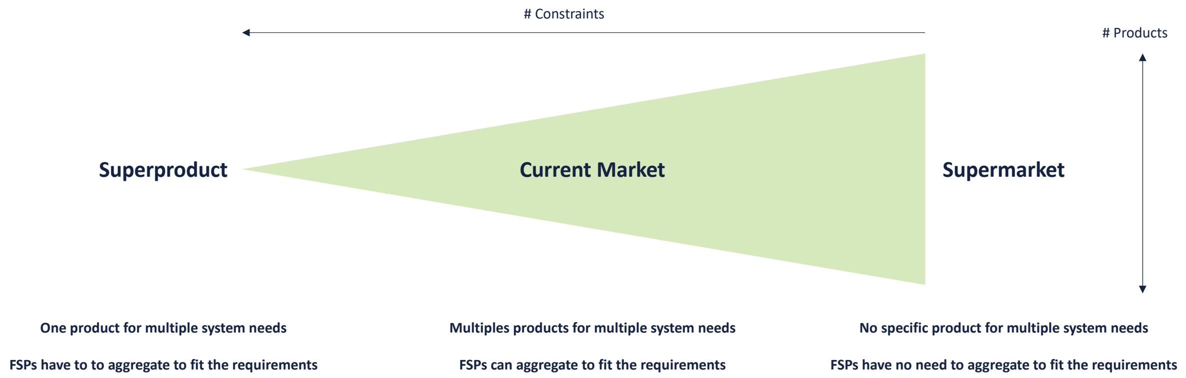


Figure 18: Generic scheme for approaches to flexibility product design specifications

### 7.1.1 Superproduct

The 'superproduct' approach assumes wide product definition which must fulfil the requirements of multiple system services and be traded on a single market. The merging of the requirements can be within a specific system service group or within a different SO's needs. The example of former approach can be joining several balancing services, e.g., electric power transmission operator in Ireland, EirGrid, uses performance remuneration with a product scalar in the financial settlement to incentivize FSPs to deliver simultaneously a bundle of services starting from Fast Frequency Response to Tertiary Operating Reserve 1 (EirGrid, 2017). The example of the latter product is Corrective Local Active Power product defined in (OneNet, 2021) that can be used simultaneously by the DSO for congestion management and by the TSO for balancing service (i.e., mFRR). The harmonization of the attribute values between multiple service needs leads to more restrictive requirements of the product specification. As a result, such a product is more difficult to attain for FSPs because the responsibility to find the optimal mix of resource capabilities to fulfil the (minimal) superproduct requirements lies on the FSP. However, the superproduct approach is more versatile to the SO' needs and allows to reduce the number of potential markets that grows in respect to the number of system requirements. In particular, the role of the market in this approach is to enable a single product clearing and consecutive distribution between the SOs.

### 7.1.2 Supermarket

The *'supermarket'* approach allows the FSP to bid the resources with diverse technical capabilities in a single market without the need to conform to the minimum requirements of the specific product attributes. In other words, it allows FSPs to have non-harmonized or non-standardized values for the minimal list of the product attributes and be considered in the market. In this approach, the optimal mix of resources that mitigate specific system scarcity is formed by the flexibility market. Such a market can be seen as a market based VPP, i.e., the VPP that is formed on the side of the market platform.

The supermarket approach comes with several challenges such as increased computational complexity, bid complexity, clearing complexity (OneNet, 2021). For instance, one of the challenges of the supermarket approach is to enable a fair marker clearing because heterogeneous products cannot be cleared using merit-order practices. In this case, the price would be defined based on the 'contribution' of the bid toward the SO requirement in a specific system service. However, the supermarket approach is technology-neutral and hence improves market liquidity by allowing access to the market for a more diverse portfolio of flexibility sources and hence reducing the potential costs of the service provision.

Ideally, the auction design will determine the efficiency of stacking various products. In such auction, the FSPs state their capability and price, while the clearing algorithm determines what volume is cleared for each product based on the optimal portfolio combination.

### 7.1.3 Current market

In both the supermarket and the superproduct approach, there is a single market that clears superproduct or multiple products for a specific requirement of SO. A current product design approach is established in between these extreme cases. In particular, the products are typically designed to accommodate the least capable unit in the portfolio of conventional resources able to mitigate a specific system scarcity and are cleared on the dedicated markets.

On one hand, sizing the service based on the technical attributes of conventional resources neglects certain excelling capabilities of the emerging technologies (e.g., fast battery storage response) and can lead to MFR oversizing and hence lower cost-efficiency. On the other hand, the technical parameters of the traditional resources are often too restrictive for modern technologies (e.g., continuous energy supply for BESSs) that prevents their separate participation in the markets.

In many cases, emerging technologies, such as renewables, battery storage and demand aggregation, that can substitute conventional resources require specific service conditions. For instance, these conditions are limited energy-content, rebound effects, or low predictability. These conditions put these technologies out of the minimum requirement for the existing products tailored to conventional resources. The liquidity of the market may be then reduced with the introduction of too strict or narrow product requirements, e.g., not making the products technology agnostic for level-playing market entry requirements of all potential participants. However, a balance shall be found between the added value of new participants in comparison to design changes to the standard products.

Therefore, the market design should prioritize the product design conditions that would be suitable for wide range of potential FSPs that bring some value to the system. These design conditions concern less strict technical parameters for products and requirements for prequalification procedure and service settlement.

### 7.1.4 Product differentiation

In pursuit of a preference toward a special type of resources, some SOs apply product differentiation (Woo, 2014) to enable participation of resources that have special characteristics or cannot comply with the minimum requirements of existing products. For instance, regional transmission organization of Pennsylvania-New Jersey-Maryland (PJM) Interconnection has differentiated their regulation ancillary service into two products, Regulation A and Regulation D, based on the speed of regulation response. Similarly, Belgian TSO, Elia, used a differentiation of symmetric Frequency Containment Reserve (R1) into R1 Sym 200 Hz, R1 Sym 100 Hz, R1 Up, and R1 Down products (ELIA, 2019). Similarly, tailored products for modern technologies with superior characteristics (e.g., fast-response battery storages) appear on the market, e.g., Fast Frequency Response services in Ireland, Australia, United States, and United Kingdom (Meng, 2019).

This approach considers the perspectives of both SO and FSP to enable *technology-neutral market design*. However, in the end, continuous differentiation of products to fit resource-specific parameters leads to a supermarket approach where specific technologies have specific product design. Moreover, extreme differentiation of the product, i.e., splitting the product per service and resource-type needs, and related market partition decrease the market liquidity and bring the risks of increased market power in relevant markets.

### 7.1.5 Suitability for geographical islands

The development of the project in the initial stages predefined the product design for the FMTP demonstration on Mayotte island toward the current market approach. This approach shaped the definition of flexibility products based on the available resources and system needs. Furthermore, flexibility aggregation through VPPs was considered as a remedy for enabling the technology-neutrality. The aggregation aims to find synergies in resource capabilities to fulfill technical needs of a system product. Such an approach is extensively used in the current market structure in continental Europe and is even more viable in the case of potentially superproduct approach.

However, when considering further generalization of the flexibility product design toward European island systems, it becomes clear that the diversity of characteristics and available resources on these islands make challenging any standardization of flexibility products. In this case, a more perspective approach is to move the innovative flexibility product design toward the supermarket approach and develop generic market mechanisms for such flexibility procurement.

## 7.2 MARKET RESTRUCTURING

The transition from the current product design to a supermarket can be achieved with market restructuring as proposed by (Bondy, 2018). The objective of the restructuring is to allow all technologies to participate in the same market and enable the SOs to optimize the procurement of the resources based upon their capabilities.

The restructuring assumes a resource-agnostic, system-aware, and performance-oriented way of market operation with the final aim of achieving *ideal tender* conditions. Such conditions mandate the use of system conditions in the market clearing, require resource-agnostic parametrization of the resource capabilities based on a list of technical attributes, and prioritize the performance-based service remuneration and auction clearing.

### 7.2.1 Joint energy-flexibility procurement

During the auction design of peak demand reduction and balancing products, a need to consider energy market results in the flexibility clearing was stated to achieve the optimal product selection. For instance, the outcome of economic dispatch is needed to determine the timing of daily peak hours where DR flexibility is required to replace peak diesel generators. Furthermore, the energy dispatch defines the available inertial level in the system and maximum reference incident that are necessary for clearing and sizing of primary frequency control products. Similarly, the energy dispatch anticipates the amount of renewable generation per specific time whose intermittency and forecast error should be considered when sizing and clearing primary and secondary frequency control products. To sum up, the system conditions defined in the energy dispatch are the input conditions for determining the volume, time, and response characteristics of required system service. Therefore, the first recommendation toward realization of the ideal tender for geographical islands is to *join the flexibility procurement and economic dispatch* into a single security-constraint unit commitment and energy dispatch (UCED) process to ensure the energy supply and reliability needs of the power system at the lowest cost under given the power system state. In such central dispatch, the energy supply, congestion management, and reserve procurement are performed simultaneously in an integrated process.

In Europe, a sequential market design for reserve and energy markets is the target model, but several studies prove the cost-efficiency of joint energy-reserve market (EU-SysFlex, 2020) in the case of increasing level of renewable generation in the total generation mix. The cost-efficiency is linearly proportional to the amount of renewable generation in the system mix but, the difference can be mitigated by dynamic dimensioning of the system reserves.

#### 7.2.1.1 Academic reference

There are several examples how such security-constraint UCED process could be organized. For instance, to integrate the primary balancing products into the SCED, a SO could determine the volume and ideal system response to a reference incident that minimizes the risk of activation of UFLS relays. One example of using ABO introduced in the previous chapter in combination with economic dispatch is presented by (Kok, 2019). Furthermore, a closed-form solution to the differential equation describing frequency dynamics is proposed by (Badesa, 2020), which allows to obtain frequency-security algebraic constraints to be implemented in optimization routines. Importantly, the article shows that droop controls can be accurately and conservatively approximated by a ramp time in a combination with an activation delay. In an article by (Zhang, 2018), ED model is proposed that extends UC model with primary and secondary frequency control requirements and their interaction with the system inertia. An article by (Teng, 2015) proposes a formulation for stochastic UC that optimizes system operation by simultaneously scheduling energy production, standing/spinning reserves, and inertia-dependent fast frequency response considering uncertainties associated with wind production and generation outages. An article (Garcia, 2021) derives MRR to ensure sufficient reserve to arrest frequency decline before reaching the critical frequency threshold while coupling primary reserve, fast frequency response, and system inertia. Finally, considering weather conditions in the reserve procurement is vital in the foreseen low carbon power systems on islands. The study in (Liang, 2022) investigates the risk-based weather-driven reserve requirement considering credible forecast errors of renewable generation. Finally, the work of (Liang Z. M., 2022) co-optimizes the procurement of energy, reserve and inertia providing services in a RES-rich power system and the pricing of these services in a centralized stochastic electricity market. The market design is based on the chance-constrained UC formulation. A potential innovation can be derived from the work on frequency dependent dynamic VPP that leverage digital filter design methods to find a perfect match of individual RPUs to the required service response in the frequency domain (Björk, 2022). The method is general and allows us to consider energy capacity, power, and bandwidth limitations.

### 7.2.2 Parameterization of resource capabilities

Instead of tendering a capacity, (Bondy, 2018) proposes a response function $V_i(t)$ that is parametrized by ramp time $t_i^r$, maximum response duration $t_i^d$, and power capacity $C_i$ for the providing unit $i$. The piece-wise linear function is then defined as follows:

$$V_i(t) = \begin{cases} \frac{C_i}{t_i^r} t, & \text{if } 0 \leq t \leq t_i^r \\ C_i, & \text{if } t_i^r \leq t \leq t_i^d \\ 0, & \text{elsewhere} \end{cases}$$

The relative capability of the resource to the required system response can be assessed based on the weighted sum of response ramping time and maximum response duration. The following is an example of the capability assessment of a resource $k_i$in relation to the required system response set of attributes $(t_0^r, t_0^d)$ proposed by (Bondy, 2018):

$$k_i = a_1 \frac{t_0^r}{max(t_0^r, t_i^r)} + a_2 \frac{min(t_0^d, t_i^d)}{t_0^d},$$

where $\sum_i a_i = 1$.

### 7.2.3 Auction clearing

In the definition of the required system response, system dynamics is considered from solving a swing equation. The equation provides the conditions for a secure post-fault frequency evolution in the case of the largest reference incident $P_L$ in a system with the inertia constant $H$ which is defined by the respective unit commitment (Badesa, 2020):

$$2\frac{H}{f_0}\frac{d\Delta f(t)}{dt} = \sum_i V_i(t) - P_L$$

The *N-1* criterion is a necessary but not a sufficient criterion for frequency stability. The sufficient system response is then defined based on the corresponding frequency-security constraints based on RoCoF, frequency nadir, and quasi-steady-state frequency. The auction clearing should fulfil the required response conditions at the lowest costs.

The clearing price can be adjusted by the capability parameter $k_i$ and reliability parameter $\gamma_i$ that is defined as an average historical performance.

### 7.2.4 Performance assessment

In the ideal tender, the performance should be evaluated not based on the minimum product definition but compared with the declared resource capabilities. The performance score is a function of the error $e_i(t)$ in service delivery:

$$\eta_i = c(e_i(t))$$
$$\eta_i = [0,1]$$

For instance, in the United States, the Federal Energy Regulatory Commission order 755 incentivizes the fair remuneration of regulation services based upon service performance.

### 7.2.5 Market remuneration

Therefore, remuneration is based upon the value the resource brings in solving the technical scarcity (i.e., resource capability), how well it performs (i.e., resource performance), and the clearing price:

$$\pi_i^{rem} = k_i \cdot \eta_i \cdot \pi_i^{clear}$$

In the version proposed by (Bondy, 2018), a pay-as-cleared pricing scheme is proposed for the ideal tender, but other options can be considered.

# 8 CONCLUSIONS

This document presented the flexibility market and product design for three use cases developed in MAESHA project, namely “Frequency control”, “Minimization of the peak consumption”, and “Voltage control”. The design is tailored to the context of geographical islands and specifically focuses on the power system of Mayotte island, department of France, where MAESHA solutions will be demonstrated. The objective of the flexibility market design in the current report was to maximize social welfare by minimizing the costs of mitigating system technical scarcities with the procurement of system services. For that, the report explained the system service specification of the developed use cases focusing on the technical scarcities that Mayotte power system currently experiences or might experience in the near future, current practices to address the scarcities, the description of the required system services including the state-of-the-art services, and further technology potential in these services. The results presented in this report aimed to address the issues of low market liquidity, vertically integrated energy market structure, design replicability, and product innovation beyond the state-of-the-art.

The methodology applied to specify the flexibility market design consists of *technical desktop analysis*, *literature review*, *qualitative and/or quantitative analyses*, *product and market composition*, and *electric utility and technology feedback* steps. For the design of flexibility market, a novel flexibility market framework was developed and described in this report. The framework provided a structure for the analysis of product and auction parts of the market design scenarios. The framework divided the task of market design into *product* and *auction* dimensions that consist of a set of stages with design attribute options. The product design describes the trading objects (e.g., technical good or service) that are traded on the market with a set of attributes, while the auction design structures the rules and mechanisms that enable trading process between the market participants to exchange flexibility products. Specification of *technical dimension* of the product and *prequalification* stage are assigned to the product design, while *procurement* and *settlement* are linked with to the auction design.

The technical scarcity of the frequency stability of island systems caused by the low inertia conditions and forecast uncertainty of renewable generation was treated with load-frequency control products of Fast Frequency Reserve, Frequency Containment Reserve, and automatic Frequency Reserve Restoration. The technical scarcity of inadequate peak generation capacity is addressed with economic-based Peak Demand Response product providing scheduled re-profiling service. Finally, the challenge of voltage stability is dealt with Volt-VaR product providing voltage-reactive power control.

Three design scenarios were considered for some stages of the auction design, including flexibility procurement, auction bidding, and auction clearing. Note that for voltage product auction, some of the stages are omitted because this product is planned to be procured through bilateral agreements between the system operator on Mayotte island and identified voltage service providers. The scenarios assessed the current flexibility management and trading practices, proposed market design that will be used in the project demonstration activities, and presented perspective market design solution that could potentially upgrade the demonstration market design in future and provide a set of recommendations for the follower islands. In particular, the *EDM-BAU* design option describes current practices of system operator on Mayotte island, *FMTP-DEMO* option shows the planned design scheme that will be tested during the project pilot demonstrations, and *FMTP-FUTURE* option provides the recommended design parameters for the auction design. The outcomes of *FMTP-DEMO* design solution will guide the final implementation of flexibility market and trading platform in work package WP7 and the implementation of the intermediary platforms (work packages WP5, WP6), and follow-up demonstration trials in the project. These design scenarios are examined toward the selected design criteria described in the methodology. The design criteria evaluated how design scenarios impact operational security improvement, low-entry market conditions to improve the market liquidity, integration complexity to the current practices of the system operator, potential socio-economic benefits, and national and European regulatory compatibility. The evaluation of the options can serve as a reference to system operator on Mayotte island and follower islands' system operators for the adoption of flexibility market in their operational planning. It is expected that the underlying market design scenarios will pave the way for business models of the different market players and provide further policy and regulatory recommendations.

Overall, *FMTP-FUTURE* design recommends applying hybrid strategy to flexibility procurement and sizing that procures and dimension the flexibility statically over long-term period and dynamically over the short-term period. Such solution would allow to prevent flexibility oversizing, improve the estimation of system conditions closer to the real-time, provide more predictability about flexibility availability to system operator, allow time-dependent resources to participate in the auctions and hence improve the auction liquidity and decrease the costs. The hybrid design option leverages the advantages of static sizing but dynamic procurement in *FMTP-DEMO* design scenario as well as static procurement and sizing in *EDM-BAU* scenario.

For the procurement mechanism, the suggested options were to use service compensation during the demonstration activities in *FMTP-DEMO* scenario and aim for competitive auction schemes in *FMTP-FUTURE* scenario if the market demonstrates sufficient liquidity. The service compensation repays the costs incurred for the provision of the service. Moreover, a hybrid compensation can be possible with part of the compensation being regulated, e.g., for capacity auction of automatic Frequency Reserve Restoration. A hybrid competition scheme can also be feasible in future where part of the flexibility price depends on the costs incurred to provide the service and part of the price is determined by the competition. This scheme would provide less risks and more predictability to potential flexibility service providers and would allow evaluation of market liquidity. For voltage auction design, however, the suggested procurement scheme would be to apply mandatory service provision as a connection of interconnection for newly installed capacity. This service could be also additionally compensated if providing extra voltage support.

The main aspect of auction clearing in *FMTP-DEMO* scenario was to suggest the usage of product scalars to estimate the value of resource on a technical scarcity the product addresses. Furthermore, for the future development in *FMTP-FUTURE* scenario, the suggested clearing product would also consider the reliability of service provision based on the historical service performance. Such performance-adjustment can also be used to modify the offer price for flexibility to motivate the service providers to improve the service provision. In *FMTP-DEMO* scenario, the suggested auction clearing would be based on merit order approach. Finally, the efficiency of the market clearing would be improved in *FMTP-DEMO* scenario if flexibility clearing would be coupled with the security-constrained unit commitment and economic dispatch.

To investigate the potential for product and market innovation of geographical islands, a high-level overview of the flexibility market design was shown based on the available approaches to the product differentiation. The report concluded that the superproduct approach is the most flexible option for island power system because of its technology-agnostic properties that fit into the diverse technology landscape of geographical islands. Furthermore, this document presented the vision for necessary energy market restructuring of geographical islands to leverage supermarket approach for the cost-efficient energy supply and guarantee necessary reliability level of system operation. The main principles of the market restructuring were summarized as a resource-agnostic, system-aware, and performance-oriented way of market operation with the final aim of achieving *ideal tender* conditions. Finally, a literature review of the academic studies enabling the balancing market and peak demand reduction was given to demonstrate the diversity of approaches that enable the target market restructuring.

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