



– Deliverable D5.4 –

Definition of Case Studies

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Executive summary

This Deliverable, which is the major output of Task T5.4, describes the main aspects that need to be considered when defining the case studies that will be used for the evaluation of the economic viability and operation performance of Dynamic Virtual Power Plants (DVPPs) under different conditions.

At a first stage, the business cases that the DVPP can follow are defined and clearly identified. Two groups of business cases are differentiated, according to the associated tool developed in previous Tasks of Work Package (WP) 5, namely (i) the tool for optimal scheduling of DVPPs under uncertainty, and (ii) the tool for optimal real-time portfolio operation.

For each of the business cases defined, different DVPP characteristics, such as configuration, location and size, are defined for later evaluation. Different electricity market rules are also identified to account for the current conditions in a variety of European power systems.

To properly set up the optimization tools for each of the conditions and scenarios defined, it is imperative to have access to the input data required. These data includes technical parameters of, e.g., the units that comprise the DVPP, and the section of the electrical grid that contains the DVPP if relevant; uncertain profiles of market prices, stochastic energy sources and demand profiles; and system-wide information such as the estimation of the market participation strategies of other market participants. This document presents several sources of publicly available data to construct the input information required by the optimization tools.

Combining the conditions and scenarios presented and discussed in this document determines the case studies to be analyzed in Tasks T5.5 and T5.6.

Finally, two methodologies to validate the performance of the optimal real-time operation tool working continuously and in actual real time are proposed.

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List of Abbreviations

aFRR	Automatic Frequency Restoration Reserve
BES	Battery Energy Storage
DAM	Day-Ahead Market
DER	Distributed Energy Resource
D-RES	Dispatchable Renewable Energy Source
DSO	Distribution System Operator
DVPP	Dynamic Virtual Power Plant
ND-RES	Non-dispatchable Renewable Energy Source
OMIE	Operador del Mercado Ibérico de Energía
PCC	Point of Common Coupling
PV	Photo-voltaic
REE	Red Eléctrica de España
RES	Renewable Energy Source
RTO	Real-Time Operation
SFR	System Frequency Response
SRM	Secondary Reserve Market
STU	Solar Thermal Unit
TSO	Transmission System Operator
WP	Work Package

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1 Introduction

1.1 Task 5.4 Overview

The fourth task of Work Package (WP) 5 defines the main aspects that are involved in the definition of appropriate case studies that will be then used in Tasks T5.5 and T5.6 to evaluate the economic viability of Renewable Energy Source (RES)-based Dynamic Virtual Power Plants (DVPPs), and their performance during close-to-real-time optimal operation, respectively.

With this aim, synthetic case studies that represent real-world scenarios are developed. The case studies consider different business cases, and represent DVPPs operating under different geographic, economic and regulatory conditions.

1.2 Objectives and Outline of the Deliverable

In Tasks T5.1 through T5.3, two tools for optimal scheduling and real-time operation of DVPPs have been developed and proposed. The detailed formulation of the models has been provided in the corresponding deliverables, and illustrative examples were also presented and discussed. These examples served a double purpose. On one hand, they illustrate the usage of the two tools from the user's perspective. On the other hand, they validate the correct implementation and performance (numerical and computational) of the models and the tools.

However, as the test cases considered in Deliverables D5.1 through D5.3 were tailored to meet the objectives above, they do not necessarily represent realistic scenarios that can demonstrate the economic viability of DVPPs in real-world applications. Moreover, the results need to be compared with those obtain from other solutions, such as the use of electrochemical Battery Energy Storage (BES) systems. Finally, a large set of scenarios under different conditions need to be tested in order to obtain reliable conclusions.

In this regard, this Deliverable proposes a comprehensive set of case studies to evaluate the viability and operation of DVPPs. To this aim, all key aspects that need to be considered when defining such case studies are carefully analyzed, and representative scenarios for each of such aspects are presented.

First, different business cases have been defined to be followed by the DVPP depending on whether the user needs to solve a scheduling problem, or a real-time operation problem. Then, different DVPP characteristics such as configuration, location, and size, as well as a variety of electricity market rules based on different European power systems, are proposed for each business case.

Case studies are then generated by appropriately combining the business cases and system characteristics. For each case, adequate data representing, as accurately as

possible, realistic scenarios, need to be retrieved, processed, and fed into the optimization tools. With this aim, different sources used to retrieve such data are presented.

Finally, to properly validate the tool for optimal real-time operation of DVPPs, two approaches are proposed to evaluate its performance when operating continuously and during relatively long periods of time, coupled with dynamic models of DVPPs and their controllers.

2 Case Studies for DVPP Viability

This section presents the main aspects that will be considered when defining the case studies to be carried out in subsequent Tasks of WP5. Such case studies are tailored with the purpose of analyzing the economic viability of RES-based DVPPs, as well as their impact when massively integrated, in a variety of scenarios by using the two optimization tools developed in Tasks T5.2 and T5.3.

The main features of the case studies include the selection of the business case chosen by the user (Section 2.1), the configuration of the DVPP (Section 2.2), the rules that the energy and/or ancillary service markets follow if an scheduling problem is solved (Section 2.3), the input data, both deterministic and uncertain, that the tools require (Section 2.4), and the size of the DVPP relative to the overall power system (Section 2.5).

Finally, Section 2.6 describes the two methodologies that will be applied to validate the optimal real-time operation tool.

2.1 Business Cases

One of the main decisions that the DVPP operator must make is the choice of the proper business case of the DVPP based on all conditions, including DVPP configuration, market structure, availability of accurate forecasts of uncertain profiles, etc. In this regard, in Deliverables D5.1 through D5.3, optimization models for DVPP optimal scheduling and operation were developed. In such models, the DVPP operator can select, by properly setting the corresponding parameters in the user interfaces of the respective tools (see Chapter 4 of D5.2 and Chapter 5 of D5.3), the business case to be optimized.

The business cases available for the DVPP operator to be selected for both scheduling and operation are briefly summarized and discussed below. In the studies that will be carried out in subsequent Tasks T5.5 and T5.6, all business cases below will be considered and thoroughly compared.

2.1.1 Scheduling

The economic viability of the RES-based DVPPs studied in the context of POSYTYF is analyzed based on the results of the scheduling problems solved by the tool for the optimal participation of DVPPs in electricity markets, which considers the different uncertainties that are inherent to the problem.

The main feature that these scheduling problems have in common is that the objective function of the optimization algorithm is the maximization of the profits obtained from participating in the markets chosen by the user. The possibilities available to the user are discussed below.

Optimal DAM Participation

As discussed in D5.1, the most important electricity market in terms of liquidity, and thus, of potential profits for the DVPP, is the Day-Ahead Market (DAM). It is possibly also the simplest to obtain an optimal schedule, as the amount of information required as input data to solve the optimization problem is substantially reduced compared to other scenarios.

Therefore, the participation of the DVPP in the DAM will be considered as a base case for the case studies concerning DVPP scheduling to be carried out in subsequent tasks. Results of other business cases will be compared with this base case.

Optimal DAM and IDMs Participation

The most common electricity market participation strategy followed by Non-dispatchable Renewable Energy Sources (ND-RESs) and other generating units characterized by a certain level of volatility in their sources such as Solar Thermal Units (STUs) is the combination of DAM and different forms of Intra-Day Markets (IDMs) (see Section 2.2.2 of Deliverable D5.1). IDMs allow such units to *adjust* their DAM offer according to more updated forecasts of their uncertain sources.

The case of the Iberian power system (Spain and Portugal) is considered as test-bed. The seven IDM sessions throughout the day give DVPPs interesting opportunities to update their original schedule while avoiding penalties of not compliance, thus increasing their economical viability. Other European market floors can also be analyzed, such as the countries managed by the Nord Pool [1].

Optimal Joint DAM, SRM and IDMs Participation

The DAM and IDMs are energy markets (i.e., blocks of electric energy and their corresponding prices are submitted as offers/bids), whose problems are usually solved independently. Simultaneous optimization of DAM and IDMs may lead to price "speculations" which, if done by all market participants, may distort the market clearance process. This is generally monitored by the corresponding market operator, and if a certain market participant is suspected of performing this practice, it can be subject to penalization.

However, other markets allow for a simultaneous optimization of the participation of, e.g., the DVPP in them together with any of the energy markets above. Currently, the clearest example are the balancing markets, whose offers/bids consist of pairs of active power (not energy) and prices (see Section 3.1 of D5.1). As opposed to the energy markets, for which cleared energy offers are expected to be delivered when scheduled, balancing markets consider the submitted active power offers as reserves, which would be called upon by the Transmission System Operator (TSO) only in the occurrence of relatively large unbalances between system generation and demand. Note however that Automatic Frequency Restoration Reserve (aFRR) are continuously activated to counterbalance generation-load unbalances.

As no adjustments of the initially offered reserves can be submitted after their clearance, no speculation is expected, and thus, the joint participation in, e.g., the DAM and Secondary Reserve Market (SRM) market is a common practice for conventional, dispatchable energy sources, which can guarantee, to a great extent, the provision of

the scheduled energy and reserve when scheduled.

The joint participation of ND-REs in both energy and balancing markets on the other hand is usually not recommended, as they generally cannot guarantee the provision of both schedules at all times due to the volatility of their energy sources. However, in the form of a DVPP, this can be achieved, with the resulting increase of profits expected compared with the two business cases discussed above.

Centralized dispatch

In general, island power systems do not incorporate market floors, but they are operated under a centralized scheme, where the system operator determines the commitment status and active power set point by means of solving Unit Commitment (UC) over different time horizons. A weekly hourly UC is followed by daily and hourly UCs to refine the solution by more recent forecasts. The UC minimizes variable operation costs, including fuel costs, operation and maintenance costs, start-up costs, etc. Recognized cost parameters are considered for this purpose. An instrumental variable cost of 10€/MWh is attached to ND-RES

The UC problem can be considered here as a special case of a price-taker approach for market-based systems. Indeed, the price-taker approach maximizes the benefits, which are defined by the difference of the incomes and the operation costs of a system, where the incomes are computed by the market price and the offered quantity. In the case of an island system, there is no price nor any connection capacity to the market, and the price-taker approach turns into a cost minimization problem. The price-taker model developed can thus be used by adding specific constraints to the security of supply.

2.1.2 Operation

Defining the optimal schedule of the DVPP by solving any of the cases listed above does not guarantee that, at the time of the power delivery, the DVPP assets will follow such schedule. This may be due to errors in the forecasted stochastic energy sources and/or demand consumption, outages of any of the units or lines, and commands from the TSO, among other reasons.

In this case, the operation of the DVPP must be also optimized near to real time in case any of the events listed above occur. This generally translates to optimization problems whose objective function is either the minimization of the deviations with respect to previously defined schedules, or the minimization of the operation costs if a internal DVPP re-dispatch is required to follow TSO commands.

Both problems, which are solved by the optimal real-time operation tool developed in Tasks T5.3 and presented in Deliverable D5.3, are briefly outlined below.

Schedule Deviation Minimization

Once the electricity (energy and power) markets have been cleared, and schedules have been defined for each participant, the DVPP must ensure that such a schedule is duly followed. However, volatility of ND-REs sources and demand consumption variations might compromise the provision of the scheduled power/energy.

A business case was proposed in Chapter 3 of Deliverable D5.3, where possible profile forecast errors of ND-REs and/or demands within the DVPP are compensated by other DVPP assets by means of an optimization problem whose objective function is the minimization of the deviations of electricity market schedules of the overall DVPP.

For each period of the schedule (typically 1 hour, although other options can also be set in the developed tool), the optimization problem is solved using the most recent forecasts of uncertain profiles, which might differ from those used to generate the market offers/bids.

Operating Cost Minimization

The Schedule Deviation Minimization business case discussed above can deal with expected forecast errors of uncertain DVPP assets at each period of the scheduled day. However, *sudden* events that might occur during each of such periods cannot be captured. Such events include TSO commands (e.g., for aFRR service provision), contingencies such as line outages, abrupt load variations, etc. To this aim, a second business case was developed in Chapter 4 of D5.3, where the objective is the minimization of the overall operating cost of rescheduling the DVPP assets to ensure that the TSO command is duly followed, or that the load variation is compensated by changing the aggregated power output of DVPP generating units.

2.2 DVPP Configuration

Another important aspect that needs to be considered when defining the case studies of Tasks T5.5 and T5.6 is the configuration of the DVPP portfolio that will be analyzed. Such configuration includes the topology of the DVPP, which defines the geographical location of its assets (Section 2.2.1), and the strategy applied to coordinate the assets, either in the form of a DVPP or with BES systems that may be installed (Section 2.2.2).

In the remainder of this section, the different possibilities that have been defined for each of the two aforementioned scenarios are presented and discussed.

2.2.1 System Topology

In Task 1.1, different possible scenarios that can be used for the analysis of realistic DVPPs in Europe have been defined. The design of the scenarios considers weather conditions and renewable resources of specific regions. Moreover, different network topologies are also accounted for, as both interconnected and isolated (island) power systems are represented.

In the case studies to be carried out in subsequent Tasks of WP5, a selection of the scenarios proposed in D1.1 will be used. Such a selection allows for a comprehensive analysis of the economic viability of DVPPs, and enables the comparison with other solutions, e.g., those based on electrochemical storage.

The scenarios from D1.1 that have been selected are briefly outlined below. Note that variations might be applied on such schemes based on each particular analysis to be performed. Said variations will be duly indicated in the corresponding description of the analysis in subsequent deliverables.

DVPP Assets within Defined Geographical Region

With regard to electricity market participation, key for the economic viability of DVPPs, European interconnected power systems are considered, as generally island systems do not incorporate market floors.

In this respect, the Spanish power system will be used for the majority of the case studies. Main reasons behind this choice include the deep knowledge of the Iberian market structure by the WP participants, the availability of abundant public data concerning prices, wind, sun and demand profiles used as inputs of the tools developed in previous tasks, and the great potential of Spain for massive penetration of RESs, with the sun as the main renewable source to be exploited (although wind generation, both on-shore and off-shore, is also expected to keep playing a key role in this regard).

The scheme proposed in D1.1 to represent a region of the Spanish power system is depicted in Fig. 2-1. The sub-network is connected to the main AC grid through a single Point of Common Coupling (PCC) (bus B5). Several renewable sources are located in the sub-network, including three Photo-voltaic (PV) plants (buses B7, B8 and B11), one wind farm (B4), one STU (B1), one hydroelectric power plant (B6), and a biomass-based plant (B9). A conventional (thermal) synchronous generating plant is also present at bus B2. Finally, five loads (buses B3, B8, B9, B11 and B12) are also defined. Typical data for this

configuration, which includes both transmission and distribution voltage levels, can be found in D1.2. In the case studies to be carried out, different RESs and flexible loads from within the sub-network are coordinated in the form of a DVPP. In [2], the DVPP included demand, hydro, PV, STU and wind generation. Note that this sub-network is not under *direct control* of the DVPP operator, as this responsibility still belongs to the corresponding TSO or Distribution System Operator (DSO).

Note also that the scheme shown in Fig. 2-1 can also be tailored to represent the characteristics of other European power systems. For instance, in D1.1, it is proposed to replace some of the solar PV plants and/or STUs with additional wind farms and hydroelectric power plants, maintaining the same sub-network topology, to represent the situation of Nordic countries. Indeed, other European zones with different primary resource availability can be analyzed with this sub-network topology. Figure 2-1 will thus be extensively analyzed in subsequent tasks.

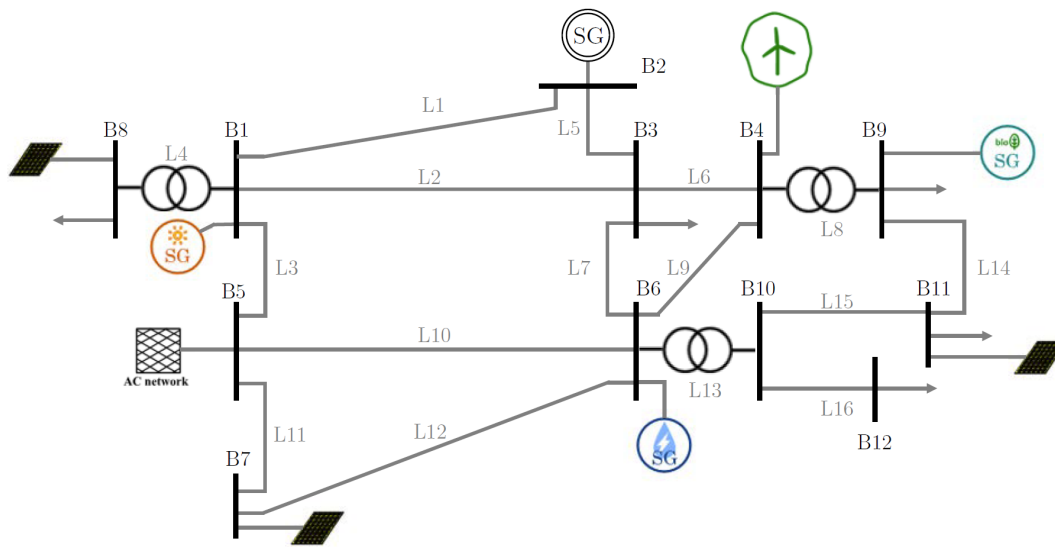


Figure 2-1 Scheme of the Southern-Europe (Spanish) 12-node sub-network

DVPP Assets Scattered Across Power System

The DVPP configuration described above is relevant as long as the DVPP assets are located in a geographically close area, where the sub-network data is available and thus can be modeled and implemented. The closer this area is, the less PCCs with the main grid would exist in the sub-network, which substantially simplifies its model. Although such network data is usually made available by the TSO or DSO to market participants, these participants have no access to network measurements or estimations (e.g., power flows). Estimation of the behavior of other user in the absence of measurement data is complicated. The consideration of the sub-network would thus mainly play a role if the DVPP owned and operated such a network.

As the DVPP assets are more spread-out, and assuming that the DVPP coordinator only has knowledge of what is electrically close, then the model approximates to a situation where only radial connections exist between the DVPP assets and the main grid, with as many PCCs as assets.

This scenario is also relevant for studies that consider price-maker DVPPs, where several RESs are coordinated in the form of a DVPP, not necessarily close to each other. In these studies, the same units as those discussed in the configuration above will be considered, upon scaling in order to ensure that the DVPP can have an impact on the cleared market price.

DVPP Assets within Island Power System

The third main topology that will be analyzed in the studies to be carried out in subsequent tasks of WP5 considers that the DVPP belongs to a power system that is isolated from any interconnected grid, i.e., islands.

The scheme proposed in D1.1 to represent an island power system can be used to a great extent. This scheme is shown in Fig. 2-2. A transmission network interconnects a solar PV plant (buses B6), one wind farm (B2), one hydroelectric power plant (B7), and a biomass-based plant (B5). A conventional (thermal) synchronous generating plant is also present at bus B1.

In Spain, several island power system exist which fit the scheme shown in Fig. 2-2. Nonetheless, ND-RESs mainly include PV and wind generation. Biomass-based plants are absent. A hydroelectric power plant exists in the island of El Hierro and another hydroelectric plant is under construction in Gran Canaria, the latter being owned and operated by the system operator.

In addition to the DVPP assets connected to the transmission network, ND-RES generation is also connected to the distribution network. If the total capacity of ND-RES generator is below 1 MW, no dispatch center is needed, and this generation is not visible to the system operator, determining the generation schedule centrally. The DVPP can uncover previously unobserved ND-RESs connected to the distribution network by aggregating them and making them visible to the system operator, determining the generation schedule centrally. Indeed, without DVPP, these resources cannot provide reserve and load-shifting services due to the lack of appropriate management and control structures.

In island power systems, the geographic availability for on-shore ND-RESs is limited. These limitations arise from other competing land uses and this usage is regulated in zoning and land use planning. There is however a large potential for off-shore wind generation.

The limited geographic availability for on-shore ND-RESs leads a limited distribution of ND-RES generation, usually concentrated around a few locations. The portfolio effect observable in continental systems is less significant, although island can exhibit very different climates (e.g., micro-climates). A single generation profile per primary energy resource type of the ND-RES is thus assumed.

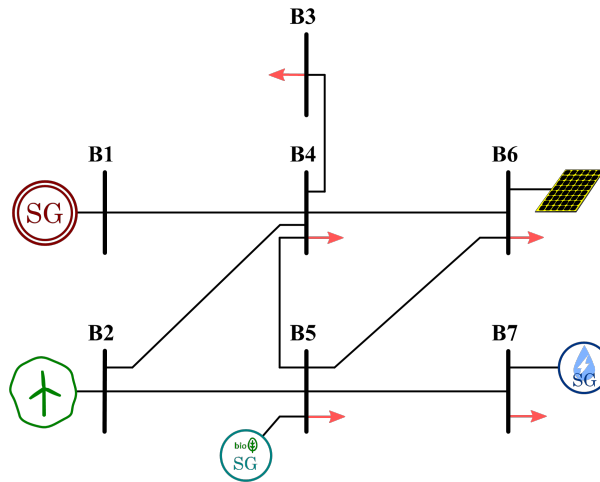


Figure 2-2 Scheme of island scenario

2.2.2 System Coordination Strategy

Once the topology for a particular study has been chosen from the selection presented in Section 2.2.1 above, the viability of the DVPP proposed in this project is compared to other solutions for that particular configuration. These solutions include two alternatives for electrochemical BES coordinated with ND-REs, as well as the case where no DVPP nor BES is implemented. The coordination strategies are briefly outlined below.

No Coordination among Assets and No BES

The reference case for the comparison is chosen as the scenario where no DVPP is configured, and no BES is installed. From the schemes shown in Figs. 2-1 and 2-2, examples of this configuration are those where all assets in the system operate independently both for bidding in the electricity market and for real-time operation. This case serves to quantify the relative increase of expected profits of the other coordination strategies in economic viability studies, as well as the benefits observed from the optimal real-time operation tool with regard to, e.g., ancillary service provision, and schedule deviation minimization.

DVPP and No BES

The second coordination strategy considers the proposed DVPP configuration. An example is depicted in Fig. 2-3 in case of an island power system. In this example, all REs are included in the DVPP, as well as the loads at buses B4 and B6, which are considered as flexible demands. On the other hand, the thermal synchronous generating unit at bus B1, as well as the loads at buses B3, B5 and B7 are not part of the DVPP, and are thus managed individually by their respective operators.

Similar approaches will be followed for the scenarios that consider large, interconnected systems, and will be described for the particular analysis in Tasks T5.5 and T5.6.

Finally, and in case of island power systems, the DVPP can uncover ND-REs by aggregating them and making them visible to the system operator, determining the generation schedule centrally.

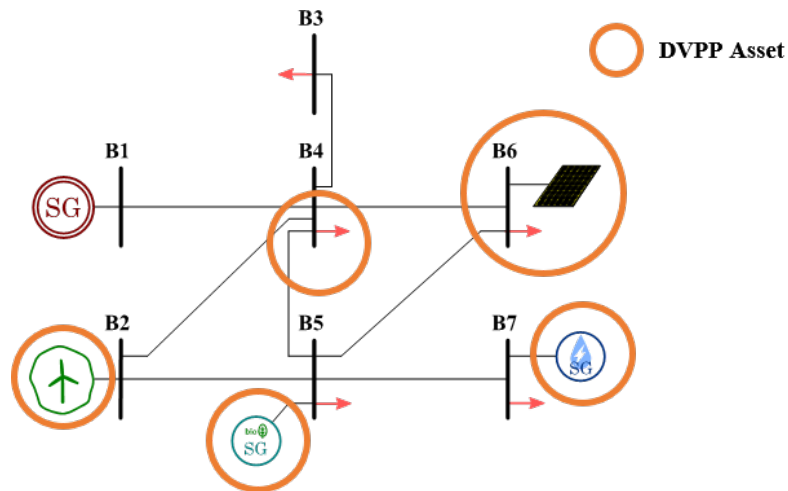


Figure 2-3 Scheme of a DVPP within an island power system

No Coordination with a Large BES

Currently, the main alternative to the proposed DVPP that appears as a solution to increase the competitiveness of ND-RESs is the electrochemical BES. In the context of WP5, BESs can improve the ND-RES economic viability by flattening their power outputs, thus minimizing any possible deviations with respect to market schedules due to forecast errors. BESs can also contribute by storing energy in periods of high renewable generation or low electricity market prices, and release it in periods of low renewable generation or high electricity market prices. BESs also help ensure the availability of reserves when requested by the system operator, which is a major concern in island power systems.

An example of this configuration is shown in Fig. 2-4 for the island scenario. A BES system is installed at bus B4 as it is the electrical barycenter of the buses with ND-RESs in the network. Different BES sizes will be compared, with capacities of, e.g., 5%, 10% and 20% of the total power capacity of the ND-RESs installed.

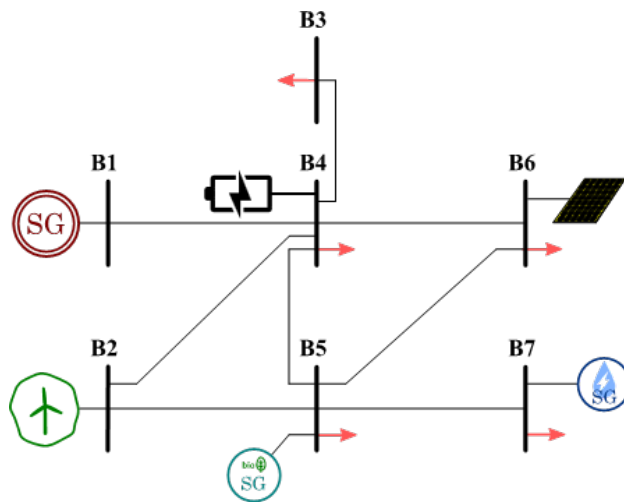


Figure 2-4 Scheme of a BES within an island power system

This configuration is a relatively common solution applied by system operators in areas that are electrically weak, e.g., areas with low inertia compared to other parts of the grid. From the economic viability analysis point of view, this means that the BES system participates on its own in energy and/or ancillary service markets, without any *a priori* coordination with any other electrically close resource.

BES Coupled to Each ND-RES

An alternative to the solution discussed above implies the coupling of a smaller BES to each of the ND-RESs in the sub-network or island. In this case, the ND-RES and BES at each bus are coordinated, and their aggregated output is then submitted as offers in electricity markets. The modularity and relatively simple installation of BESs of any desired size at almost any orographic location makes this configuration another promising solution to increase the competitiveness of ND-RESs by largely reducing their inherent volatility.

This configuration is illustrated in Fig. 2-5, where two BES systems are connected to buses B2 and B6 to operate together with the wind farm and solar PV plant, respectively. For this scenario, it is considered that each pair of ND-RES and BES participate, as a single unit, in the energy and ancillary service markets modeled.

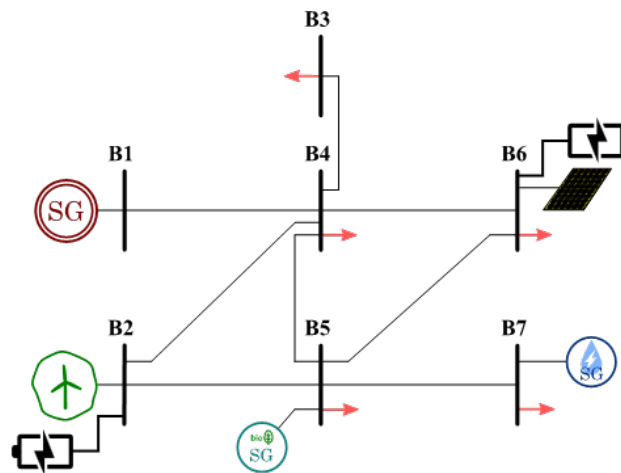


Figure 2-5 Scheme of an island power system with a BES coupled to each ND-RES

2.3 Market Conditions

In Section 2.6 of Deliverable D1.3, a review of the details of the structure of energy and ancillary service markets of different European countries was presented. Among these characteristics, two are of particular relevance for the case studies and results comparisons that will be conducted in subsequent tasks, namely:

- **Aggregation allowance:** it indicates whether it is permitted to aggregate a set of assets in order to comprise an offer/bid unit in the market or not; and
- **Heterogeneity allowance:** it defines whether it is permitted to construct an aggregator composed of Distributed Energy Resources (DERs) and RESs of different technologies, or if instead all assets in the aggregator should be of the same technology.

To understand whether a DVPP solution is viable, a comprehensive and thorough analysis considering different market conditions (i.e., different countries), needs to be carried out. With this aim, the most representative possibilities for aggregation of RES and flexible demands in the form of a DVPP are listed and briefly outlined below.

No Aggregation Allowed

This is the reference case for the comparisons of the results of the case studies, as discussed in Section 2.2.2 (see *No Coordination among Assets and No BES* subsection). This is the case, for instance, of France for the aFRR service, as seen in Table 7 of D1.3.

Only ND-RESs Allowed

Other countries only allow aggregation of assets of the same primary energy resource, such as the Spanish balancing markets. In this scenario, a group of ND-RESs of the same primary energy resource (e.g., the three PV plants from Fig. 2-1) will be coordinated as a DVPP.

D-RESs and ND-RESs Allowed (No Flexible Demand)

A less restrictive regulatory framework allows the aggregation of generating units of any technology, or flexible demands, i.e., aggregation of flexible demand and generation in the same pool is not allowed.

This scenario will be represented in the case studies as a DVPP where only generating RESs will be integrated. The main difference with respect to the previous case above is the capability of aggregating generating units of different technologies, e.g., wind farms, solar PV plants, STUs, hydroelectric power plants and/or biomass power plants.

RESs and Flexible Demand Allowed

The last scenario concerning market conditions and regulatory constraints considers the case where any aggregation is allowed. In this case, generating RESs and flexible demands can operate in a coordinated manner to submit single offers in energy and ancillary service markets.

2.4 Input Data

In Section 5 of Deliverable D5.1, the importance of a proper characterization of the parameters of the models included in the tools developed in this WP was introduced and justified. The goal of this parameter definition is to construct synthetic case studies that are, nevertheless, accurate representations of *realistic* scenarios.

In particular, Table 5-1 of D5.1 presents a list of the main parameters that need to be defined in the models developed for optimal scheduling under uncertainty, and real-time optimal operation. In the table, two main families of data can be identified, namely:

- the technical parameters of DVPP resources and, if modeled, the sub-network. These parameters are deterministic, i.e., they are not time-dependent; and
- the uncertain, time-dependent profiles of stochastic renewable sources, energy and ancillary service markets, and demand consumption.

The process to define both parameter types in the case studies of subsequent tasks are briefly discussed below. Note that the values of all deterministic parameters and uncertain profiles will be provided in following deliverables, as these will not be unique for all case studies to be carried out, but rather, they will be specific of each scenario.

2.4.1 Deterministic Data - DVPP Parameters

Deliverables D1.1 through D1.3 propose sets of deterministic data to be used for the case studies of other WPs. In particular, data of the different network configurations discussed in Section 2.2 above, as well as typical capacities of the Dispatchable Renewable Energy Sources (D-RESs) and ND-RESs are provided in the aforementioned documents.

Technical parameters of mature RESs (hydro power plants, solar PV plants, wind farms), such as ramp limits, different operation costs, and efficiencies, can be easily defined for each of these technologies and any capacity, as abundant data sheets can be found from manufactures and public agencies [3, 4, 5]. Moreover, industrial partners within POSYTYF have also contributed in the parametrization of the developed models, particularly of less mature or widely-used technologies.

Among the different RES technologies that are considered as potential assets of the DVPP studied in this project, the STU with storage has arguably the most convoluted model (see Sections 3.3.6 through 3.3.8 of Deliverable D5.2). Some works can be found which include technical data of STUs in the literature (e.g., [6]). For the sake of illustration, the data of a 55 MW STU, based on a real-world, plant located in Southern Europe, is provided below. These data would be appropriately scaled if STUs of other capacities are used in the case studies.

Table 2-1 Data of a 55 MW STU

Parameter	Value & Units
Total thermal capacity	128 MW (thermal)
Maximum electrical power output	55 MW
Maximum rate-of-change of electrical power output	10% of full capacity/min
Powerblock breakpoints (for piece-wise linear efficiency curve)	[0, 19, 40, 70, 140]
Bounds for piece-wise linear efficiency curve	[0, 0.3, 0.35, 0.38, 0.39]
Thermal storage capacity	1100 MWh (thermal)
Thermal storage charging power capacity	140 MW (thermal)
Thermal storage discharging power capacity	115 MW (thermal)
Thermal efficiency of storage heat exchanger	99%
Operation & maintenance costs	20 €/MWh
Start-up costs ¹	500 €

¹ The start-up costs of the STU also include the corresponding shutdown costs.

2.4.2 Uncertain Data Profiles

The second type of data required as inputs of the two optimization tools developed in this WP takes the form of time-dependent uncertain profiles. Three main subfamilies can be defined, namely market prices, stochastic energy sources, and demand consumption. Being time-dependent, it is thus crucial to have large sets of representative profiles if comprehensive analysis and comparisons are to be carried out. Such sets should consider seasonality, geographical location and demand characteristics, among other features. To this aim, public repositories by regulatory agents, market operators, distribution and weather companies, and governments are essential. In the remainder of this section, some of the sources used to generate the uncertain profiles for the case studies of subsequent Tasks are presented.

Prices

Historical data of energy and ancillary service market prices are usually made available by European system operators and market regulators. Sophisticated information systems allow the user to select the time interval for which the cleared prices of the chosen market are displayed. This data can either be analyzed from graphs generated in the information systems, or downloaded as data files for further processing.

In the case of the Iberian system (Spain and Portugal), the market operator (OMIE) and the TSO (Red Eléctrica de España - REE) are responsible of making available the results of the market auctions. In particular, historical data of DAM and IDMs can be found in the market operator's website, [7], whereas results of secondary reserve auctions can be found in REE's site [8]. Figures 2-6 through 2-8 illustrate the graphs that the user can generate in the aforementioned websites for the DAM, first IDM session, and SRM, respectively.



Figure 2-6 Prices and traded energy at DAM in Iberian energy market - September 14, 2022. Source: [7]

Information of other European markets can be obtained from several sources, such as [1] for Nordic Countries (e.g., Norway, Finland, Sweden, Denmark, Estonia, Latvia, and Lithuania); [9] for the all-island Irish system; and [10] for Italy.

Stochastic Energy Sources

The second main source of uncertainties in the models developed in this WP is related to the stochastic sources of the ND-RESs that comprise the DVPP (i.e., wind speed and solar irradiation). Contrary to the electricity market prices, which usually are equal for the overall system under study, stochastic sources are location-dependent. Thus, different profiles need to be defined if different geographic locations are considered. Although some organizations provide historical data of the overall wind and/or solar generation in a particular system (e.g., [11], finding public sources of historical data of specific plants is rather convoluted. Moreover, reliable forecasts of stochastic energy sources for such particular locations are difficult to obtain.

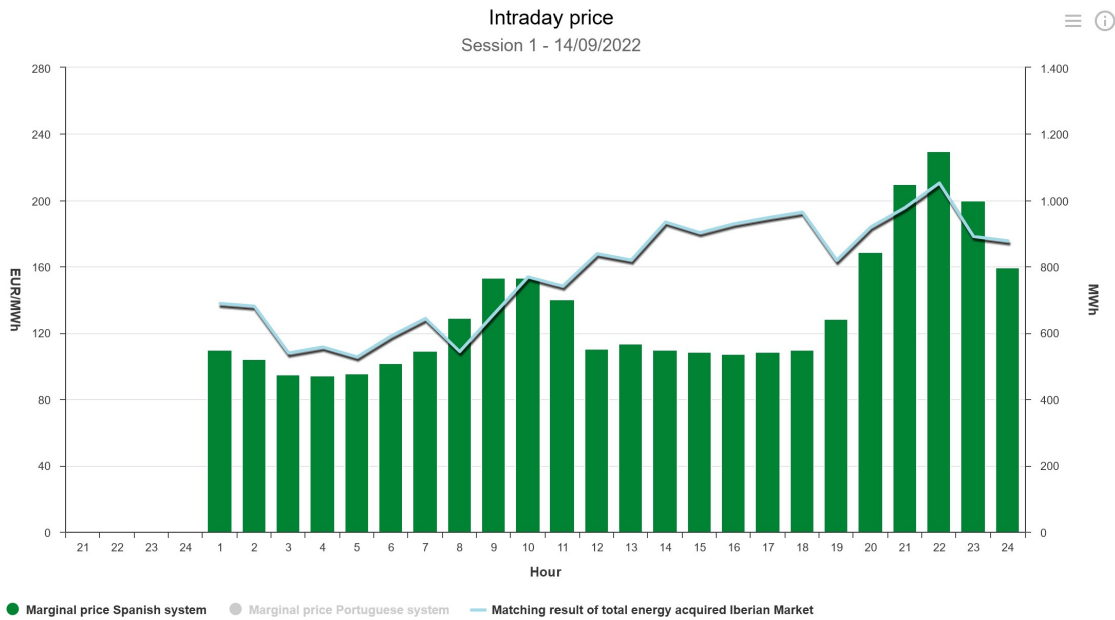


Figure 2-7 Prices and traded energy at IDM#1 in Iberian energy market - September 14, 2022. Source: [7]



Figure 2-8 Prices of upward and downward reserve in Iberian SRM - August 2022. Source: [8]

To cope with this issue, for the case studies to be carried out in this WP, historical and forecast data of wind power and solar irradiation provided by POSYTYF partners IBERDROLA GENESP and CIEMAT, respectively, will be used. An example of such data is shown in Fig. 2-1 of Deliverable D5.2, which is recalled below in Fig 2-9. The hourly distributions shown in the figure are generated, by means of a forecasting tool developed by project partner CIEMAT, prior to each of the energy markets modeled, i.e., DAM, SRM and all IDMs sessions in the Iberian system. The location chosen corresponds to an STU located in the south of Spain (see Fig. 2-1 of this document).

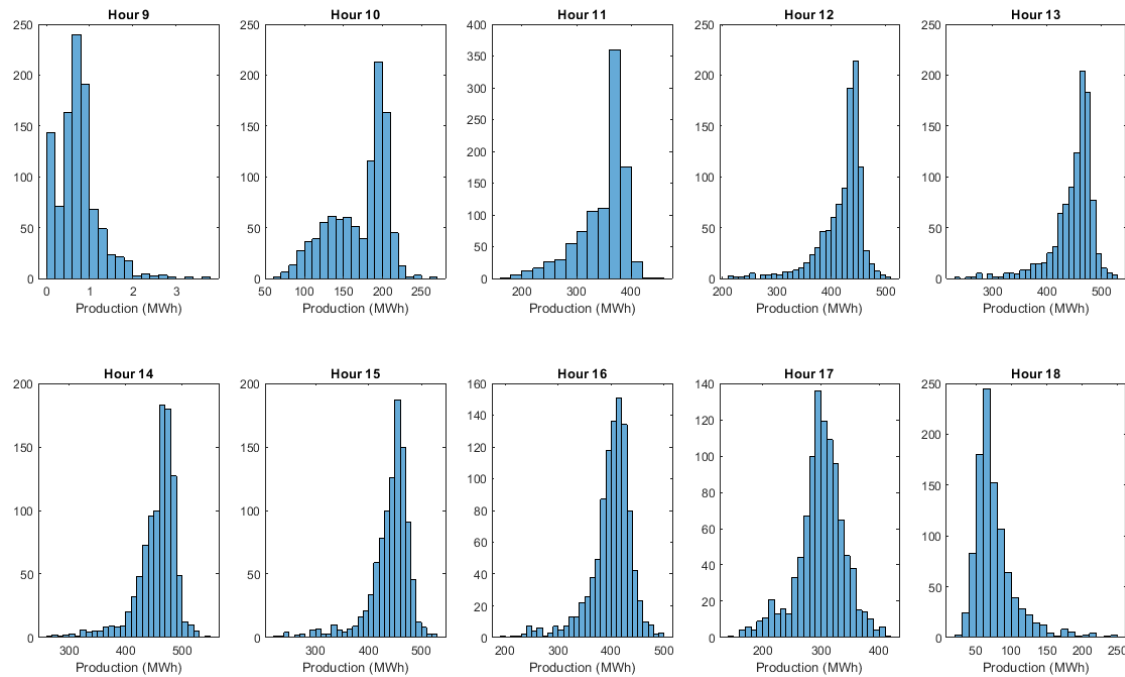


Figure 2-9 Histograms of probabilistic forecasts of the energy available at the solar field of an STU in Spain on December 9, 2018

In case of island power systems, at least on representative weekly ND-RES profile per primary resource type will be initially considered. Daily historical profiles with down to 5 minutes resolution can be found within REE's web application on real-time demand information [12]. Figure 2-10 shows the demand and aggregated ND-RES generation of the island power system of Gran Canaria on September 26, 2022. Additional hourly and daily ND-RES profiles can be downloaded from [13]. To cope with future installed capacities of ND-RESs, different scenarios will be considered (for instance, current, 5 x current, 10 x current) [14].

Demand Profiles

Finally, for the case of demand consumption, forecasted and actual profiles can be found, for instance, within REE's web application on real-time demand information [12]. Figure 2-11 shows and compares scheduled demand, forecasted demand and real demand of the island power system of La Palma on September 26, 2022. Future demand projections will be considered according to the future scenarios of installed ND-RES capacities (see also [14]).

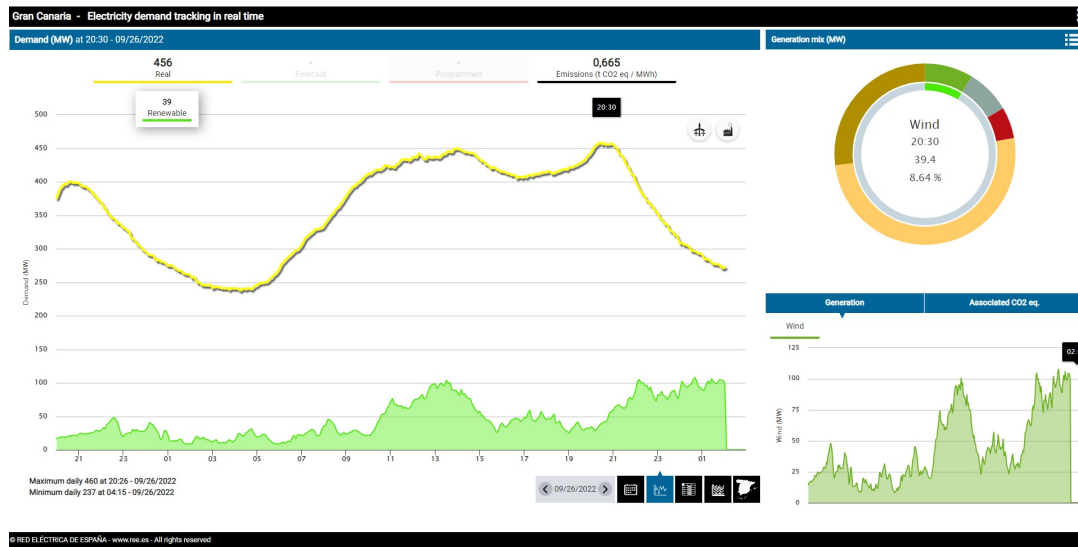


Figure 2-10 Demand and aggregated ND-RES generation of the island power system of Gran Canaria - September 26, 2022. Source: [12]



Figure 2-11 Demand forecast, scheduled demand, real demand and aggregated ND-RES generation of the island power system of La Palma - September 26, 2022. Source: [12]

2.5 DVPP Size

The size (i.e., the aggregated capacity) of the DVPP is a key feature that needs to be carefully defined in the case studies that are discussed in this document. Although the DVPP size could have been discussed in Section 2.2, which presents the main aspects concerning the configuration of the DVPP portfolio, a specific section has been dedicated to this crucial feature.

Concerning the optimal scheduling of the DVPP that participates in electricity markets, apart from the differences in the results of the optimization problems when considering and comparing DVPP of different sizes, if the aggregated capacity of the DVPP is *big enough*, the nature of the problem (and its complexity) changes substantially. In this context, the two main problems that are identified depending on the size of the DVPP analyzed, namely the Price Taker problem and the Price Maker problem, are discussed in Sections 2.5.1 and 2.5.2, respectively.

The size of the DVPP is also expected to have a significant impact on the optimal real-time operation problems that are considered in the case studies. Larger DVPPs allow for more efficient re-dispatch options against any contingency or errors in the forecasts of uncertain profiles. This aspect is discussed in Section 2.5.3

2.5.1 Price-Taker

The preliminary results presented in Deliverables D5.1 through D5.3, consider that the DVPPs simulated have an aggregated capacity that is *small* compared with the total capacity of the overall power system. In this case, the DVPP has negligible market power, i.e., the DVPP has little to no impact on the cleared market prices, regardless of the offers/bids submitted by the DVPP. In this case, the DVPP profits will depend exclusively on the other market participants. This is commonly known as a *price taker* problem.

Market operators and regulators usually prevent aggregators from becoming price makers, as this translates typically into higher market prices by executing market power, thus negatively impacting consumers. Therefore, it is expected that price-taker DVPPs will be the most common situation for these aggregators. However, defining the threshold that differentiates between being a price taker or a price maker is rather complex, as it is system and time dependent (as total load consumption varies throughout the day). Moreover, there is always a subjective component when defining such a threshold, i.e., there is no exact and unique value of the DVPP beyond which it becomes a price maker.

In this context, the case studies that are carried out in Task T5.5 considers price-taker DVPP portfolios of different aggregated capacity to analyze how the expected profits of the optimal scheduling problem vary in accordance. Increasing DVPP capacities will be modeled either by adding RES units and/or flexible demands, and by increasing the capacities of the units of the reference DVPP portfolio. To this aim, the overall system capacity will always be taken into account to ensure that the relative size of the DVPP with respect to the overall system is always under the threshold. For instance, in Spain the largest generators have a capacity of up to 1000 MW, and considering DVPP sizes around this value is reasonable (e.g., DVPP of 250 MW (similar to [2]), 500 MW, and 1000 MW).

2.5.2 Price-Maker

If the aggregation of RESs and flexible demands results in a DVPP of a significant size, i.e., comparable to other large market participants, then the DVPP will have an impact on the cleared market prices, i.e., it becomes a *price maker*.

When the DVPP is aware of its own market power, the profit maximization of the optimal scheduling problem will naturally tend to alter the price to achieve this objective. Being a price maker thus shows clear advantages in terms of competitiveness of the DVPP against other market participants with respect to the price maker approach.

However, the market clearance prices also depend on other market participants, which follow similar individual profit maximization objectives. The optimal DVPP scheduling problem thus becomes a multi-level problem, where in the first level the DVPP tries to maximize its profit, whereas in the second level the clearing of the market is solved by assuming that the DVPP knows the offers/bids of the other market participants. In other words, cost and utility functions of the remaining generator and demand agents of the market must be known. Although typical values for the techno-economic parameters including the cost function parameter exist in the literature (e.g., [15]), the actual values are not publicly available. In such a case, missing data need to be synthetically generated, i.e., need to be *guessed*, which, to some extent, represents realistically how market participants with market power generate their offers/bids.

Therefore, being a price maker increases substantially the complexity of the problem.

2.5.3 Centralized Dispatch and Operation

Regarding island power systems, the DVPP can uncover previously unobserved ND-RESs connected to the distribution network by aggregating them and making them visible to the system operator. The total ND-RES within the DVPP is a fraction of current and future system-wide ND-RES (for instance, 10%-20%-40% per primary energy resource type). D-RES within the DVPP is a fraction of the total ND-RES of the DVPP (for instance, 0%-10%-20%). Note that combined cycle power plants of around 220 MW are the largest units in the larger Spanish island power systems, corresponding to 40% of the peak demand.

The same DVPP sizes will be used to assess the operation cost minimization applied to the aFRR service provision in island power systems (see subsection 2.1.2).

Finally, when a centralized dispatch is carried out in island power systems, recognized cost parameters are considered to solve the UC. Reference [16] contains the relevant techno-economic parameters of conventional generation as well as D-RES and ND-RES generation.

2.6 Co-Simulation Studies

The tool for optimal scheduling of DVPP is usually run once per market window, with a handful happening each day. Therefore, computational constraints are usually not an issue in this type of problems. However, the tool for real-time DVPP portfolio optimization needs to be run repeatedly and continuously over time, in a reliable and swiftly manner. To test and validate the performance of this real-time optimal operation tool under these conditions, co-simulation studies will be carried out to simulate the provision of ancillary services by the DVPP. In particular, the ancillary service considered is secondary frequency control.

The secondary frequency control is a system-wide control in charge of activating the resources providing aFRR. In general, the secondary frequency control is a hierarchical control where a central proportional+integral (PI) controller issues active power set points to individual units by means of participation factors. These participation factors distribute the control effort among the units. The participation factor of each unit typically depends on the fraction of each unit's secondary reserve to the total hourly aFRR. In case of Spanish island power systems, the participation factor of each unit is however at least such that its secondary reserve is proportional, in terms of the available capacity, to the total hourly aFRR.

The performance of the secondary control in an island power system with a DVPP will be analyzed. It is assumed that the solution of a generation scheduling problem has assigned a fraction of the total hourly secondary reserve to the DVPP. The secondary control will be simulated by using different dynamic simulation platforms: a simplified Simulink-based System frequency response (SFR) model and a Simulink-interfaced Dynamic Real-Time Simulation Tool. A Real-Time Operation (RTO) algorithm of the DVPP will be embedded in these simulation platforms. The objective of this RTO algorithm is precisely the minimization of the overall operating cost of rescheduling the DVPP assets to ensure that the secondary control set point is duly followed (see Section 4 of Deliverable D5.3).

Standard data per generation technology (turbine-governor system, boiler, rotor, etc.) will be used to parameterize the model (see [17, 18]). Non-synchronous ND-RES responses will be assumed to be much faster than synchronous generation responses (D-RES or conventional). However, wind generation may have significant delays after partial shut down of a wind farm (re-orientation of the nacelle, etc.).

Interaction between WP5' Optimal Real-Time Operation Tool and WP3' Secondary Control Algorithms

The simulation of the secondary frequency control will consider at least fundamental frequency dynamics of the island power system by making use for instance of SFR models, based on uniform frequency. The RTO algorithm of the DVPP will be incorporated into the secondary control simulator of the island system. The performance of the secondary control to fast and slow ramp changes will be analyzed. The deviation caused by the ramps will not exceed the total hourly secondary reserve of the island power system. Figure 2-12 shows an SFR model of an island power system including the DVPP's RTO. Figure 2-12 implements the *direct* secondary frequency control proposed in the Deliverables D3.1 and D3.2.

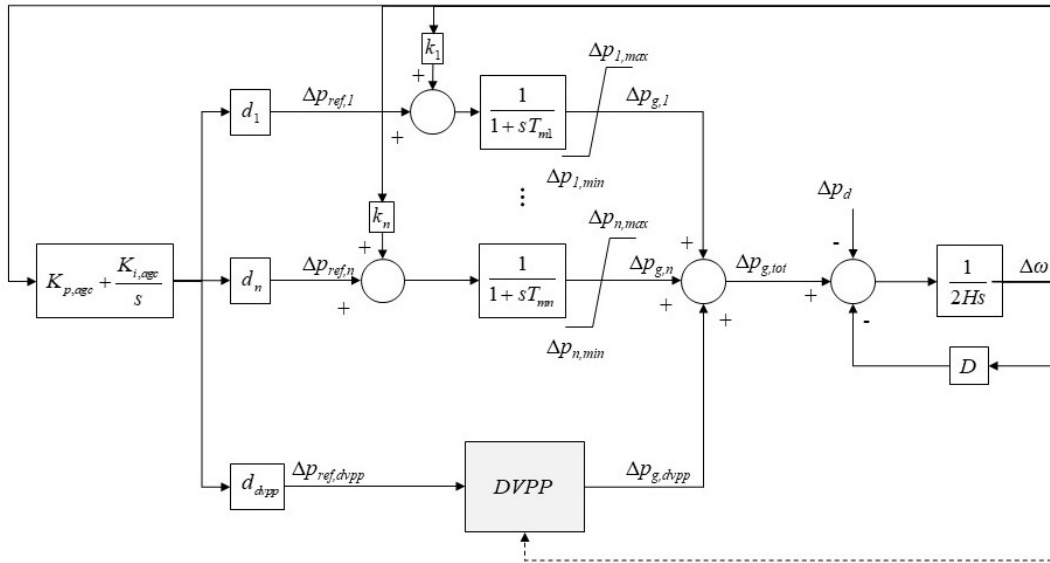


Figure 2-12 SFR model of an island power system including the DVPP's RTO

Interaction between WP5' Optimal Real-Time Operation Tool and a Dynamic Real-Time Simulation Tool

To go a step further and analyze the operation of the RTO algorithm in a more realistic environment, the RTO algorithm will be coupled with a Simulink-interfaced Dynamic Real-Time Simulation Tool. For this purpose, the island power system will be simplified in a first instance to a single equivalent variable voltage source, representing the overall island generation, to which the DVPP will be connected by means of an equivalent impedance. This is similar to the benchmark system proposed in the Deliverable D3.2 to test the proposed *direct* secondary frequency control. Figure 2-13 illustrates a Simulink model for the Opal-RT-based real-time simulation of the RTO algorithm.

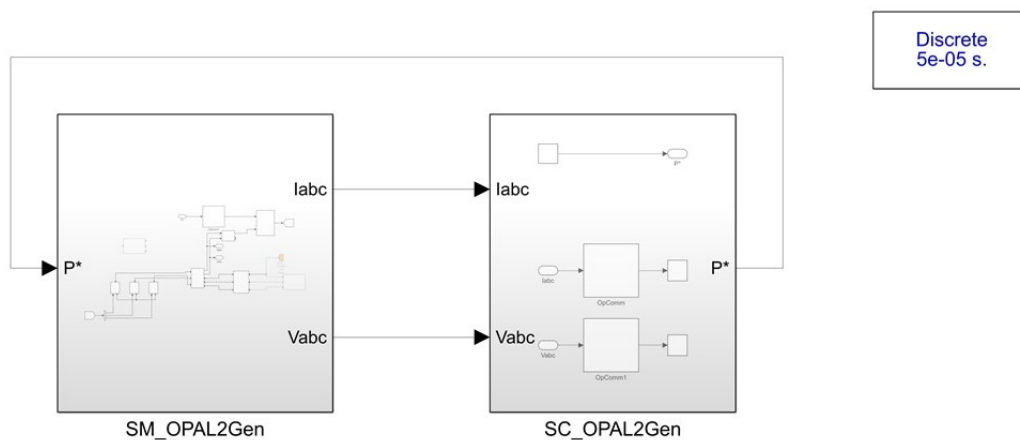


Figure 2-13 Illustration of the opal-RT model including the DVPP's RTO

3 Conclusions and Future Work

This Deliverable concludes Tasks T5.4 and presents the methodology to be followed in subsequent tasks of this WP5 to generate the case studies that will be carried out to evaluate the economic viability and operation performance of the RES-based DVPP proposed in POSYTYF project.

To analyze the economic viability of DVPPs, which is the main objective of Task T5.5, four business cases are proposed to be later studied and compared, three of which are designed for interconnected power systems with a market sequence defined, and a fourth business case for isolated power systems in which no market is implemented.

Different market rules can be found when analyzing the electricity market structures of European countries. Complying with such rules has a direct impact on the results of the business case applied. In this regard, a selection of the most representative market conditions have been identified, with different levels of flexibility when aggregating assets for market participation. The market rules defined will be studied for the different business cases proposed for interconnected power systems.

Another relevant aspect that will be carefully analyzed in the viability studies is the size of the DVPP relative to other market participants. In this regard, different aggregated capacities of the DVPP will be considered in the case where the DVPP has little to no market power, thus following the market price cleared by other participants. In addition, the possibility that the DVPP is large enough to be able to alter the cleared market price by strategically preparing its offers/bids is also considered.

The results of the viability studies discussed above will be compared with other alternative and widely-applied solutions, such as the use of electrochemical BES systems to increase the competitiveness of ND-RESs. To this aim, different configurations of BESs coupled with the ND-RESs that otherwise would be part of the DVPP have been proposed for comparison.

Regarding the focus of Tasks T5.6, i.e., the analysis of the impact of a massive integration of DVPPs on system operation and ancillary service needs, two business cases are defined. In this case, isolated (island) power systems are of particular relevance, as aggregation of generating units and flexible demands can easily represent a large share of the total capacity of the island system. In this regard, different DVPP configurations, coordination strategies and sizes have also been proposed, similarly to the viability studies above, to generate a comprehensive set of case studies.

To properly analyze the impact on the operation and ancillary service provision of DVPPs, co-simulation case studies have been designed in which the the tool for real-time DVPP portfolio optimization is continuously run over significant periods of time in a simulation environment where the optimization algorithm is coupled in real time with a dynamic model of an island power system. The secondary frequency control strategies for DVPPs developed in WP3 will be implemented in this co-simulation platform.

For both Tasks T5.5 and T5.6, the case studies proposed can only be carried out if adequate input data is available to feed the two DVPP optimization tools developed in previous tasks. Input data includes technical parameters of, e.g., the units that comprise the DVPP; uncertain profiles of market prices, stochastic energy sources and demand profiles; and system-wide information such as the estimation of the market participation strategies of other market participants. This document presents a selection of sources from European agencies, system operators and regulators, distribution and weather companies. Such data enable the development of case studies that, although synthetic, are accurate representations of real-world scenarios.

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