



– Deliverable D5.2 –

Tool for the Optimal Operation of DVPPs under Uncertainty of Non-dispatchable RES

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Executive summary

In Task 5.1, the core of a novel Renewable Energy Source (RES)-based Dynamic Virtual Power Plant (DVPP) model that optimizes its operation and configuration when participating in European energy and ancillary service markets was proposed. Such a Dynamic Virtual Power Plant (DVPP) model comprises different business cases by properly defining the objective function of the optimization model such that the DVPP selectively participates in one or more of the three markets considered, namely Day-Ahead Market (DAM), Secondary Reserve Market (SRM) and Intra-Day Markets (IDMs).

One limitation of the DVPP model core proposed in D5.1 is that it assumes that the forecasts of a priori uncertain data, such as market prices and stochastic energy sources (wind speed and solar irradiation), are *exact*. However, this is a strong assumption that generally does not correspond to reality. In fact, in the majority of cases, the longer the time horizon considered to determine the optimal schedule of the DVPP, the lower the accuracy of such forecasts.

This document presents an update of the DVPP model core, where uncertainties are duly taken into account for determining the optimal participation of the DVPP in the different markets considered. This is achieved by implementing the so-called Robust Optimization, which solves the optimization problem for the *worst-case realization* of the uncertain range.

Compared to other existing techniques that tackle the uncertainty problem, the Robust Optimization shows significant advantages such as the possibility to define, from the user's side, the boundaries of the uncertain range based on the strategy to follow, whether optimistic, neutral, or pessimistic. Other advantages include the relatively simple format of the uncertain input data required by the Robust Optimization algorithm, where only the median and upwards/downwards deviations of the uncertain distributions need to be defined.

This document also describes in detail the tool developed to parameterize, execute and visualize results from the optimization algorithm. The operation and performance of the tool is discussed by means of a comprehensive set of illustrative examples that serve to validate the tool proposed.

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List of Abbreviations

BESS	Battery Energy Storage System
DAM	Day-Ahead Market
D-RES	Dispatchable Renewable Energy Source
DVPP	Dynamic Virtual Power Plant
ESS	Energy Storage System
GAMS	General Algebraic Modeling Language
IDM	Intra-Day Market
MILP	Mixed Integer Linear Programming
ND-RES	Non-dispatchable Renewable Energy Source
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Source
SG	Synchronous Generator
SOS	Special Order Set
SR	Market
SRM	Secondary Reserve Market
STU	Solar Thermal Unit
TES	Thermal Energy Storage
TSO	Transmission System Operator
WP	Work Package

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1 Introduction

1.1 Task 5.2 Overview

The second task of Work Package (WP) proposes a tool that has been developed as an update of the Dynamic Virtual Power Plant (DVPP) model core that was formulated in Task 5.1. The tool allows the user to determine the optimal participation of the DVPP in one or several energy and ancillary service markets considering the uncertainties that characterize some of the input data required by the model, such as market prices and stochastic, non-dispatchable Renewable Energy Sources (RESs).

1.2 Objectives and Outline of the Deliverable

Uncertainty management in power system optimization problems is a necessary but rather complex task. Given the large amount of uncertain profiles that characterize power systems (market prices, localized wind speeds and solar irradiation, demand consumption, etc.), to ensure problem feasibility while obtaining meaningful results from the optimization algorithm is of utmost importance.

With this regard, this Deliverable presents the set of techniques applied to the DVPP model core proposed in D5.1 to account for the uncertainties involved in the problem. The result is an efficient and user-friendly tool that provides the optimal DVPP offer for participating in the selected market session for the flexible worst-case realization of the uncertainty range. This way, any actual realization of uncertain parameters would lead to equal or better results than the optimal solution obtained.

The most significant advantage of the tool proposed is that the uncertainty range is modular and can be defined by the DVPP operator. In other words, the user can define, for each uncertain profile and based on their forecast probabilistic distributions, the desired *budget of uncertainty*. This allows the DVPP operator to follow different strategies, whether optimistic (small budgets represent low uncertainty allowance), pessimistic (large budgets to obtain higher possible deviations with respect to the forecast), and neutral.

1.3 Structure of the Deliverable

The remainder of this Deliverable is organized as follows.

Chapter 2 provides an overview of the different uncertainties that characterize the RES-based DVPP developed in this project, and the need to duly model them for the studies carried out. Main features of the uncertain profiles, such as the asymmetry in their distributions, are highlighted. Finally, the approach considered to model uncertainties in the optimization algorithm, namely the Robust Optimization, is outlined.

Chapter 3 provides the detailed formulation of the robust optimization model for DVPPs participating in energy and ancillary service markets. Uncertainties in the objective function as well as in the constraints are described separately. The robust optimization model is an upgrade of the DVPP model core developed in Task 5.1 and presented in Deliverable D5.1.

To ensure a simple and efficient interaction between the user and the tool proposed in this document is crucial. In this regard, a detailed user manual of the proposed tool is provided in Chapter 4. The user-friendly interface of the proposed tool, developed using MS Excel is thoroughly presented.

Simple case studies that illustrate the operation and performance of the robust optimization algorithm are presented and discussed in Chapter 5.

Finally, Chapter 6 draws conclusions, and outlines future work directions in the WP.

2 Optimal Participation of DVPPs in Electricity Markets Under Uncertainties - An Overview

In Deliverable D5.1, a model that determines the optimal participation of a DVPP in typical European electricity markets (including energy and ancillary service markets) was proposed. The DVPP model included Dispatchable Renewable Energy Sources (D-RESs) (e.g., hydroelectric power plants), Non-dispatchable Renewable Energy Sources (ND-RESs) (e.g., solar photovoltaic (PV) plants, wind farms), Solar Thermal Units (STUs) (which share features of D-RESs and ND-RESs), and flexible demands. The business models considered, i.e., the objective functions of the optimization model, are the maximization of the total profits (revenues minus costs) of the DVPP participation in one or more of the aforementioned markets. Several examples were also shown and discussed to illustrate the performance and benefits of the model.

The main limitation of the DVPP model proposed in D5.1 is that it provides a *solution to a deterministic problem*. In other words, it assumes that the forecasts of, e.g., the prices of electric energy and ancillary services and stochastic sources such as wind and solar irradiation, are *exact*. However, this assumption is generally far from true, specially as longer time horizons are forecasted. For instance, to determine the optimal participation of a DVPP in the Day-Ahead Market (DAM) and Secondary Reserve Market (SRM), the model requires the forecasts of the DAM and SRM prices, as well as the wind and solar available power of any ND-RES or STU that may be part of the DVPP. Such forecasts typically cover a time window of 13 through 36 hours ahead of the market closure time (see Sections 2.2 and 5.2 of Deliverable D5.1).

This is illustrated in Fig. 2-1, where the forecasts of the available thermal production at the solar field of an STU in South Spain on December 9, 2018 is represented. The forecasts were generated by a simulation platform developed by POSYTYF partner CIEMAT [1]. One thousand simulations were carried out to determine the possible scenarios for the day selected based on real-world measured data from the plant, and the histograms of each of these simulations for all hours of the day have been generated. The predictions were made 13 hours prior the first delivery period. The night hours are not included in Fig. 2-1, given their low relevance for the illustration.

Two main observations can be remarked from Fig. 2-1. On one hand, the assumption of *exact* forecasts, although needed when developing the DVPP model core proposed in D5.1, it is not valid for real case studies. Although for each hour there is always a value that shows the greatest probability of actual realization, the possible deviations around such values are generally not negligible, both in terms of the value of the deviation itself in MWh, and the probability of occurrence. On the other hand, the histograms, which in practice represent the uncertainty bounds of the solar power available at the STU, are generally non-symmetric. In fact, the asymmetry varies between hours, with some hours showing a distribution "shifted" to the right, others to the left, and some are close to a normal distribution.

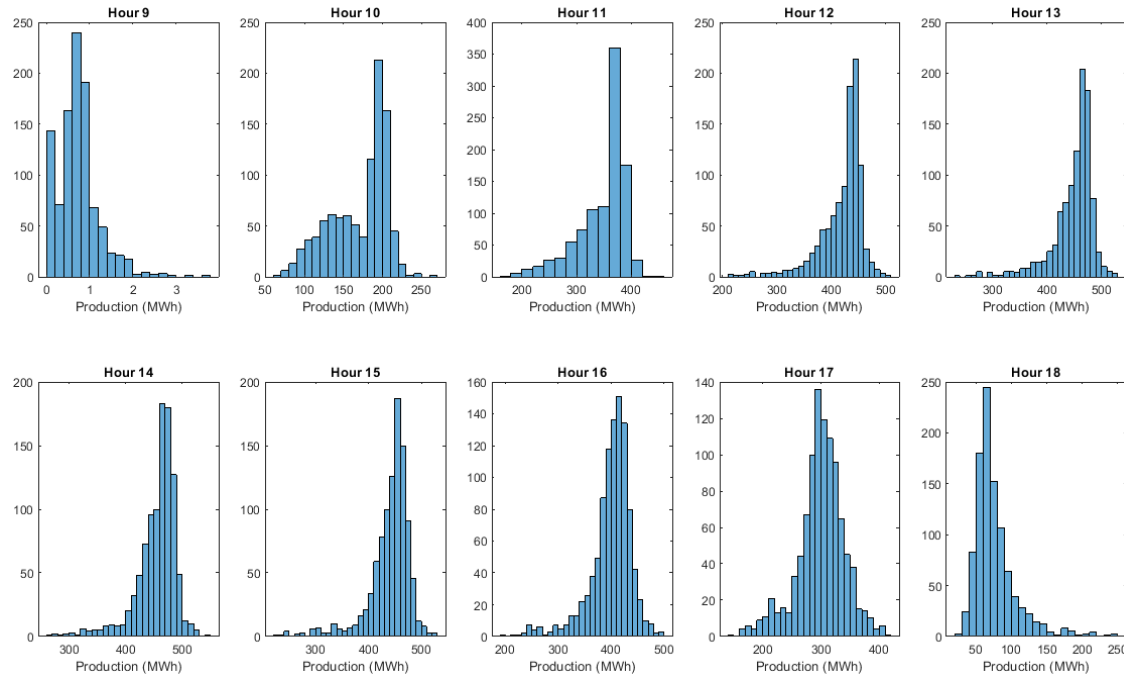


Figure 2-1 Histograms of probabilistic forecasts of the energy available at the solar field of an STU in Spain on December 9, 2018

Similar remarks can be drawn if the histograms of the uncertainties of prices of the different markets, as well as of the wind power production and even demand consumption. With this in mind, it can be easily deduced that, to consider all relevant sources of uncertainties in the problem at hand, although necessary, is not a trivial matter. To this aim, different techniques to consider different uncertainties in optimization problems are available in the literature. Among these, the most extended are arguably the *Stochastic Programming* [2, 3, 4, 5, 6] and the *Robust Optimization* [7, 8, 9, 10, 11]. In this work, the latter has been implemented in the DVPP model. The rationale behind this decision was provided in Appendix B of D5.1.

2.1 Overview of Robust Optimization of DVPPs

Based on the considerations discussed above, the robust optimization has been implemented in the DVPP model that is being developed in this WP. In particular, the following parameters have been considered to be characterized by uncertainty:

- DAM prices;
- SRM prices (both upwards and downward reserve);
- Intra-Day Markets (IDMs) prices (e.g., 7 IDM windows in the Spanish case);
- available power production of ND-RESs; and
- available power production at the solar field of STUs.

To define the uncertain nature of the parameters above, it is needed to define the *median* of the distribution of forecast values, and the maximum and minimum deviation

around this median that the uncertain parameter could take. Therefore, the value X_t that an uncertain parameter can take at a given time t is generally defined as follows:

$$X_t \in [\tilde{X}_t - \check{X}_t, \tilde{X}_t + \hat{X}_t], \quad \forall t \in \mathcal{T} \quad (2.1)$$

where $\tilde{X}_t$ is the median of the distribution, $\check{X}_t$ and $\hat{X}_t$ are the maximum downwards and upwards deviations around the median, and $\mathcal{T}$ is the set of time periods. Taking as an example hour 16 of Fig. 2-1, the thermal power production that the solar field is expected to provide is:

$$P_{\theta,16} \in [\tilde{P}_{\theta,16} - \check{P}_{\theta,16}, \tilde{P}_{\theta,16} + \hat{P}_{\theta,16}] = [406 - 213, 406 + 63], \quad (2.2)$$

2.1.1 Robust Optimization on Objective Function

The majority of the implementations of robust optimization in virtual power plant applications is based on the principles that Bertsimas and Sim presented in [7]. In their work, the authors initially proposed a nonlinear, bi-level problem to tackle uncertainties of parameters in the objective function (mainly energy and ancillary services prices). However, this process can be converted into a single-level, Mixed-Integer Linear Programming (MILP) problem by applying the duality principle. This is the starting point of the formulation considered in this work, and is illustrated in (2.3) for a symmetric distribution of uncertainties in the objective function.

$$\left. \begin{array}{l} \max \sum_t C_t x_t \\ \text{s.t. :} \\ Ax = B \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \max \sum_t \tilde{C}_t x_t - \Gamma^o \nu^o - \sum_t \eta_t^o \\ \text{s.t. :} \\ \nu^o + \eta_t^o \geq \hat{C}_t y_t^o; \quad \forall t \\ -y_t^o \leq x_t \leq y_t^o; \quad \forall t \\ Ax = B \\ \nu^o, \eta_t^o, y_t^o \geq 0; \quad \forall t \end{array} \right. \quad (2.3)$$

Deterministic problem
Robust formulation

where x_t is the vector of decision variables; A and B are matrices of fixed parameters; t is the time index representing hours; C_t is the vector of uncertain parameters; Γ^o is a user defined parameter that represents the robust uncertainty budget in the objective function; ν^o and η_t^o are dual variables related to the sensitivity of the solution to the parameter value deviation; and y_t^o is the dual variable related to the absolute value of x_t .

As it can be observed from (2.3), robust flexibility on optimization is implemented using a parameter Γ^o that *adjusts* the level of robustness that the user chooses for each uncertain parameter. In a way, this *uncertainty budget* Γ^o represents the number of time periods for which an uncertain parameter will take the value that has the most negative impact on

the objective function. For instance, for a net seller DVPP, prices will take the lowest value in the interval in (2.2), whereas for a net buyer DVPP, prices will take the highest value of the interval.

The *uncertainty budget* Γ^o can thus take any value between zero, which corresponds to the deterministic case without volatility, and the number of periods of the market horizon, T , for which the parameters takes the worst value from the objective function point of view in all periods in the market horizon. For instance, for the DAM, uncertain parameters would take values between 0 and 24. If Γ^o takes any intermediate value between 0 and T , then the optimization algorithm will choose the Γ^o periods for which the worst realization of the uncertain parameter would impact the most on the objective function. For the remaining $T - \Gamma^o$ periods, the uncertain parameter would be deterministic, i.e., $X_t = \tilde{X}_t$. If non-integer values for Γ^o are chosen, then a fraction of the last period in which uncertainty is included would be considered. With this formulation, the user can then choose the strategy to follow, either optimistic (low values of Γ^o), or conservationist (high values of Γ^o).

2.1.2 Robust Optimization on Constraints

In Section 2.1.1 above, a solution to deal with uncertainties in the objective function of an optimization problem was highlighted. In the context of the DVPP studied in this WP, typical uncertain parameters that are found in the objective function of the problem are the electricity market prices (both energy and ancillary services). However, prices are not the only source of uncertainty in this problem. Volatility of ND-RESs and STUs needs also to be taken into account. However, these uncertain parameters appear in the optimization constraints, which further convolutes the problem and its formulation.

The robust formulation applied to the uncertain parameters in the optimization constraints is illustrated in (2.4),

$$\underbrace{x_t \leq X_t; \quad \forall t}_{\text{Deterministic problem}} \rightarrow \left\{ \begin{array}{ll} x_t \leq \tilde{X}_t - y_t^c; & \forall t \\ y_t^c \leq \tilde{X}_t; & \forall t \\ y_t^c \geq \nu^c + \eta_t^c - \max_{tt} \{ \tilde{X}_{tt} \} (1 - \chi_t); & \forall t \\ \nu^c + \eta_t^c \geq \tilde{X}_t; & \forall t \\ \varepsilon \chi_t \leq \eta_t^c \leq \max_{tt} \{ \tilde{X}_{tt} \} \chi_t; & \forall t \\ \sum_t \chi_t \geq \Gamma^c & \end{array} \right. \quad (2.4)$$

Robust formulation

where X_t is the vector of uncertain parameters delimiting the upper bounds of the vector of optimization variables x_t ; Γ^c is a user defined parameter that represents the robust uncertainty budget in the optimization constraints; ν^c and η_t^c are dual variables related to the sensitivity of the upper bound value to the robust uncertainty budget; y_t^c represents the downwards deviation of the uncertain parameter; ε is a very small positive number;

and χ_t is a binary variable that guarantees the level of robustness that was required by the user through Γ_c ($\chi_t = 1$ if for period t the uncertain parameter deviates with respect to the median value).

As uncertainty is affecting the available power production of ND-RESs and STUs, the scenario that shows the most negative impact on the objective function is that for which, for a given period, the uncertain parameter takes the lowest value of its interval, i.e., $X_t = \bar{X}_t - \bar{X}_t$. In other words, upwards deviation of ND-RESs and STUs available power is not considered in the robust optimization problem.

The set of constraints in the right-hand side of (2.4) needs to be defined for each source of uncertainty in the constraints, i.e., one for each ND-RES and STU unit i that the DVPP comprises. This implies that the DVPP operator needs to define as many Γ_i^c as ND-RESs and STUs are included in the DVPP. As opposed to Section 2.1.1, each Γ_i^c can only take integer values between 0 and the number of periods in the scheduling horizon. The higher Γ_i^c is, the more periods in the scheduling horizon include this uncertainty in the model, and thus, the more pessimist the solution is. This is one of the main novelties of the proposed model with respect to previous works proposed in the literature, where the user generally needs to define one uncertainty budget for each stochastic DVPP unit i , and for each time period t (e.g., [11, 10]). In these works, each $\Gamma_{i,t}^c$ is bounded between 0 and 1, with 0 being the exact forecast and 1 the most pessimist case.

This implies that, if a DVPP comprises for instance three ND-RESs, and is solving the problem to determine the optimal participation in the DAM, then the user would need to define the uncertainty budget for the price, Γ^o , and 72 (3×24) $\Gamma_{i,t}^c$. The formulation proposed in this document, on the other hand, only requires the definition of Γ^o and 3 $\Gamma_{i,t}^c$, which greatly simplifies the utilization of the optimization tool.

The detailed formulation of the robust optimization of a DVPP participating in electricity markets under uncertainty is provided in Chapter 3, where all concepts highlighted in the Sections above are thoroughly discussed.

3 Robust Optimization of a DVPP Participating in Energy and Secondary Reserve Markets - Model Formulation

This chapter collates the nomenclature and set of constraints which the DVPP uses to participate in energy (DAM and IDMs) and reserve (SRM) markets. This chapter gives an update of Chapter 4 in Deliverable D5.1 on "DVPP Objective Function and Components". While we do not regurgitate the information from the D5.1 here, we add some clarifying notes on the constraints set forth in the following sections.

3.1 Nomenclature

To aid easier reading of the constraints, the reader should keep the following general concepts about the notation in mind.

- Variables are represented with lowercase letters, a ;
- parameters are written in UPPERCASE letters (exceptions are parameters represented with Greek letters), A , α ;
- the tilde symbol on uncertain parameters indicate the the median value of the forecast distribution (i.e., the value for which 50% observations take lower values), $\tilde{A}$;
- the hat (inverse hat) symbol on uncertain parameters indicate the maximum positive (negative) deviation allowed with respect to the most likely value of the forecast, $\hat{A}$ ($\check{A}$);
- upper bars on parameters depict upper bound of variables, $\bar{A}$;
- lower bars on parameters mean lower bound of variables, $\underline{A}$;
- upward (downward) arrows indicate up (down) direction of regulation in regulation variables, costs and reserve provision, $a^\uparrow$, $A^\uparrow$, $(a^\downarrow, A^\downarrow)$; and
- positive (negative) signs, $+$ ($-$), as superscripts of variables or parameters indicate charging (discharging) states of Energy Storage Systems (ESSs), a^+ , A^+ , (a^-, A^-) .

3.1.1 Indexes and sets

Symbol	Description
$b \in \mathcal{B}/\mathcal{B}_m$	Network Buses/network buses connected to main grid
$c \in \mathcal{C}/\mathcal{C}_b$	Conventional, D-RESs/D-RESs connected to bus b
$d \in \mathcal{D}/\mathcal{D}_b$	Demands / demands connected to bus b
$i(\ell)/j(\ell)$	Sending/receiving-end of line ℓ
$k \in \mathcal{K}$	IDM sessions
$\ell \in \mathcal{L}/\mathcal{L}_b/\mathcal{L}_m$	Network lines/network lines connected to bus b /to main grid
$p \in \mathcal{P}$	Daily load profiles
$r \in \mathcal{R}/\mathcal{R}_b$	Stochastic ND-RESs / ND-RESs connected to bus b
$s \in \mathcal{S}/\mathcal{S}_b$	ESSs/ESSs connected to bus b
$t \in \mathcal{T}$	Time periods
$v, v' \in \mathcal{V}$	SRM calls on condition by DVPP operator
$\psi \in \Psi$	Set of D-RESs, ND-RESs, STUs, demands and ESSs
$\theta \in \Theta/\Theta_b$	STUs / STUs connected to bus b
Ξ^{DA}	Set of decision variables of DAM
Ξ^{ID}	Set of decision variables of IDMs
Ξ^{SR}	Set of decision variables of SRM

3.1.2 Parameters

Symbol	Description	Unit
C_c^0/C_c^1	Shut-down/start-up cost of D-RES c	[€]
C_c^V	Variable production cost of D-RES c	[€]
$C_{d,p}$	Cost of load profile p of demand d	[€]
C_r^M	Operation and maintenance costs of ND-RES r	[€]
C_s	Total unit cost of ESS s , including installation and expected operational costs	[€]
DO_c/UP_c	Number of periods D-RES c has been offline/online prior to the first period	[hour]
DO_θ/UP_θ	Number of periods STU θ has been offline/online prior to the first period	[hour]
DT_c/UT_c	Minimum down/up time of D-RES c	[hour]
DT_θ/UT_θ	Minimum down/up time of STU θ	[hour]
$\bar{E}_d$	Minimum energy consumption of demand d throughout the planning horizon	[MWh]
$\bar{E}_s$	Energy capacity of ESS s	[MWh]

$\underline{E}_{s,t}/\bar{E}_{s,t}$	Lower/upper bound of the energy stored in ESS s during time period t	[MWh]
F^{SR}	Maximum Secondary Reserve (SR) calls on duration time divided by duration of one whole period	[—]
K_{θ}	STU θ output multiplier at startup	[—]
M_s	Slope of the linear approximation of the expected life of Battery Energy Storage (BES) s as a function of the cycles	[—]
$N_c^{\text{off}}/N_c^{\text{on}}$	Number of initial periods during which D-RES c must be offline/online	[hour]
$N_{\theta}^{\text{off}}/N_{\theta}^{\text{on}}$	Number of initial periods during which STU θ must be offline/online	[hour]
$\bar{P}_b$	Maximum power that the DVPP can trade with the main grid at bus b	[MW]
$\underline{P}_c/\bar{P}_c$	Minimum/maximum power production of D-RES c	[MW]
$P_{d,p,t}$	Maximum hourly consumption of profile p of demand d during time period t	[MW]
$\underline{P}_{d,t}/\bar{P}_{d,t}$	Lower/upper bound of the power consumption of demand d during time period t	[MW]
$\bar{P}_{\ell}$	Active power capacity of network line ℓ	[MW]
$P_{r,t}^{\text{DA}}$	Available power production of ND-RES r at DAM during time period t	[MW]
$P_{r,t}^{\text{SR}}$	Available power production of ND-RES r at SRM during time period t	[MW]
$P_{k,r,t}^{\text{ID}}$	Available power production of ND-RES r at IDM# k during time period t	[MW]
$\underline{P}_s^+/\bar{P}_s^+$	Lower/upper bound of charging capacity of ESS s	[MW]
$\underline{P}_s^-/\bar{P}_s^-$	Lower/upper bound of discharging capacity of ESS s	[MW]
$\underline{P}_{\theta}/\bar{P}_{\theta}$	Minimum/maximum power production capacity of STU θ	[MW]
$\underline{P}_{\theta}^+/\bar{P}_{\theta}^+$	Lower/upper bound of charging capacity of STU θ	[MW]
$\underline{P}_{\theta}^-/\bar{P}_{\theta}^-$	Lower/upper bound of discharging capacity of STU θ	[MW]
$P_{\theta,n}^{\text{PB}}$	Bound defined in each piece-wise linear function n of the power block of STU θ	[MW]
$P_{\theta,t}^{\text{DA}}$	Available power production of STU θ at DAM during time period t	[MW]
$P_{\theta,t}^{\text{SR}}$	Available power production of STU θ at SRM during time period t	[MW]
$P_{k,\theta,t}^{\text{ID}}$	Available power production of STU θ at IDM# k during time period t	[MW]
$\underline{R}_c/\bar{R}_c$	Down/up ramping limit of D-RES c	[MW/h]
$\underline{R}_c^0/\bar{R}_c^1$	Shut-down/start-up ramping limit of D-RES c	[MW/h]
$\underline{R}_c^{\text{SR}}/\bar{R}_c^{\text{SR}}$	SR down/up ramp rate of D-RES c	[MW/min]
$\underline{R}_d/\bar{R}_d$	Down/up ramping limit of demand d	[MW/h]

$\underline{R}_d^{\text{SR}} / \bar{R}_d^{\text{SR}}$	SR down/up ramp rate of demand d	[MW/min]
$\underline{R}_r^{\text{SR}} / \bar{R}_r^{\text{SR}}$	SR down/up ramp rate of ND-RES r	[MW/min]
$\underline{R}_s^{\text{SR}} / \bar{R}_s^{\text{SR}}$	SR down/up ramp rate of ESS s	[MW/min]
$\underline{R}_\theta^{\text{SR}} / \bar{R}_\theta^{\text{SR}}$	SR down/up ramp rate of STU θ	[MW/min]
S^B	System power base	[MVA]
T	Last period of schedule	[–]
T^{SR}	Required time for SR action	[min]
U_c^0	Initial commitment status of D-RES c (1 if it is generating electricity, 0 otherwise)	[0/1]
X_ℓ	Reactance of network line ℓ	[Ω]
$\underline{\alpha}_s / \bar{\alpha}_s$	Lower/upper bound multiplier of ESS s at last period of schedule	[–]
γ_s	Self-discharge value of ESS s over a 24-hour period	[%]
Γ^{DA}	Uncertainty budget of DAM price	[–]
Γ_k^{ID}	Uncertainty budget of the price of IDM session k	[–]
$\Gamma^{\text{SR},\uparrow} / \Gamma^{\text{SR},\downarrow}$	Uncertainty budget of up/down SRM price	[–]
Γ_r^{DA}	Uncertainty budget of ND-RES r available energy in the DAM	[–]
$\Gamma_{r,k}^{\text{ID}}$	Uncertainty budget of ND-RES r available energy in IDM session k	[–]
Γ_r^{SR}	Uncertainty budget of ND-RES r available energy in the SRM	[–]
$\Gamma_\theta^{\text{DA}}$	Uncertainty budget of solar field energy of STU θ in the DAM	[–]
$\Gamma_{\theta,k}^{\text{ID}}$	Uncertainty budget of solar field energy of STU θ in IDM session k	[–]
$\Gamma_\theta^{\text{SR}}$	Uncertainty budget of solar field energy of STU θ in the SRM	[–]
Δt	Duration of time periods	[hour]
ε	Very small (positive) value	[–]
η_s^+ / η_s^-	Charging/discharging efficiency of ESS s	[%]
$\eta_\theta^+ / \eta_\theta^-$	Charging /discharging efficiency of the thermal storage of STU θ	[%]
$\eta_{\theta,n}$	Conversion factor between thermal and electrical power in piece-wise linear function n of the power block of STU θ	[%]
λ_t^{DA}	DAM price during time period t	[€/MWh]
$\lambda_{k,t}^{\text{ID}}$	Price of IDM session k during time period t	[€/MWh]
$\lambda_t^{\text{SR},\uparrow} / \lambda_t^{\text{SR},\downarrow}$	SRM up/down price during time period t	[€/MW]

3.1.3 Continuous Variables

Symbol	Description	Unit
$c_{c,t}^0/c_{c,t}^1$	Auxiliary variable used to linearize the shut-down/start-up cost of D-RESs c during time period t	[€]
c_s^{deg}	Degradation cost per cycle of Battery Energy Storage System (BESS) s	[€]
$e_{s,t}$	Energy stored in ESS s during time period t	[MWh]
$e_{\theta,t}$	Energy stored in STU storage θ during time period t	[MWh]
$p_{b,t}^m$	Active power scheduled to be bought from (+)/sold to (−) the DAM and IDM markets at bus b during time period t	[MW]
$p_{c,t}$	Active power generation of D-RESs c during time period t	[MW]
$p_{d,t}$	Active power consumption of demand d during time period t	[MW]
$p_{v,\ell,t}$	Active power flow through network line ℓ during time period t for calls on condition v by DVPP operator	[MW]
$p_{r,t}$	Active power generation of ND-RES r during time period t	[MW]
$p_{s,t}$	Active power output of ESS s during time period t (positive if discharging)	[MW]
$p_{s,t}^+/p_{s,t}^-$	Charging/discharging power level of ESS s during time period t	[MW]
p_t^{DA}	Total power traded in the DAM during time period t	[MW]
$p_{k,t}^{\text{ID}}$	Total power traded in the k -th IDM session during time period t	[MW]
$p_{\theta,t}$	Active power output of STU θ during time period t	[MW]
$p_{\theta,t}^{\text{PB}}$	Active power sent to the power block of STU θ during time period t	[MW]
$p_{\theta,t}^{\text{SF}}$	Active power output of the solar field of STU θ during time period t	[MW]
$p_{\theta,t}^+/p_{\theta,t}^-$	Charging/discharging power level of STU storage θ during time period t	[MW]
$r_{b,t}^{\text{SR},\uparrow}/r_{b,t}^{\text{SR},\downarrow}$	Up/down SR provided by DVPP at the main grid bus $b \in \mathcal{B}_m$ during time period t	[MW]
$r_t^{\text{SR},\uparrow}/r_t^{\text{SR},\downarrow}$	Total up/down reserve traded in the SRM by DVPP during time period t	[MW]
$r_{v,b,t}^{\text{SR}}$	SR provided by DVPP at the main grid bus $b \in \mathcal{B}_m$ during time period t for calls on condition v by DVPP operator	[MW]
$r_{v,c,t}^{\text{SR},\uparrow}/r_{v,c,t}^{\text{SR},\downarrow}$	Up/down SR provided by D-RES c during time period t for calls on conditions v by DVPP operator	[MW]
$r_{v,d,t}^{\text{SR},\uparrow}/r_{v,d,t}^{\text{SR},\downarrow}$	Up/down SR provided by demand d during time period t for calls on conditions v by DVPP operator	[MW]
$r_{v,r,t}^{\text{SR},\uparrow}/r_{v,r,t}^{\text{SR},\downarrow}$	Up/down SR provided by ND-RES r during time period t for calls on conditions v by DVPP operator	[MW]

$r_{v,s,t}^{\text{SR},\uparrow} / r_{v,s,t}^{\text{SR},\downarrow}$	Final up/down SR provided by ESS s during time period t for calls on conditions v by DVPP operator	[MW]
$r_{v,s,t}^{\text{SR},+, \uparrow} / r_{v,s,t}^{\text{SR},+, \downarrow}$	Up/down SR provided by ESS s while in charging state during time period t for calls on conditions v by DVPP operator	[MW]
$r_{v,s,t}^{\text{SR},-, \uparrow} / r_{v,s,t}^{\text{SR},-, \downarrow}$	Up/down SR provided by ESS s while in discharging state during time period t for calls on conditions v by DVPP operator	[MW]
$r_{v,\theta,t}^{\text{SR},\uparrow} / r_{v,\theta,t}^{\text{SR},\downarrow}$	Final up/down SR provided by STU θ during time period t for calls on conditions v by DVPP operator	[MW]
$r_{v,\theta,t}^{\text{SR},+, \uparrow} / r_{v,\theta,t}^{\text{SR},+, \downarrow}$	Up/down SR provided by STU θ while in charging state during time period t for calls on conditions v by DVPP operator	[MW]
$r_{v,\theta,t}^{\text{SR},-, \uparrow} / r_{v,\theta,t}^{\text{SR},-, \downarrow}$	Up/down SR provided by STU θ while in discharging state during time period t for calls on conditions v by DVPP operator	[MW]
$x_{\theta,t,n}$	Non-negative auxiliary, continuous variable in SOS-2 formulation	[-]
y_t^{DA}	Dual variable related to the uncertainty of the DAM price	[MWh]
$y_{k,t}^{\text{ID}}$	Dual variable related to the uncertainty of the price of IDM session k	[MWh]
$y_t^{\text{SR},\uparrow} / y_t^{\text{SR},\downarrow}$	Dual variable related to the uncertainty of the up/down SRM price	[MW]
$y_{r(\theta)}^{\text{DA}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) available energy in the DAM	[—]
$y_{k,r(\theta)}^{\text{ID}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) energy in IDM session k	[—]
$y_{r(\theta)}^{\text{SR}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) energy in the SRM	[—]
$\delta_{v,b,t}$	Voltage angle at bus b during time period t for calls on condition v by DVPP operator	[rad]
η_t^{DA}	Dual variable related to the uncertainty of the DAM price during time period t	[€]
$\eta_{k,t}^{\text{ID}}$	Dual variable related to the uncertainty of the price of IDM session k during time period t	[€]
$\eta_t^{\text{SR},\uparrow} / \eta_t^{\text{SR},\downarrow}$	Dual variable related to the uncertainty of the up/down SRM price during time period t	[€]
$\eta_{r(\theta),t}^{\text{DA}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) available energy during time period t in the DAM	[€]
$\eta_{k,r(\theta),t}^{\text{ID}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) energy during time period t in IDM session k	[MWh]
$\eta_{r(\theta),t}^{\text{SR}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) energy during time period t in the SRM	[MWh]
$\sigma_s^{\text{SR},\uparrow} / \sigma_s^{\text{SR},\downarrow}$	Share of energy capacity of ESS s allocated to provide up/down SR	[%]
ν^{DA}	Dual variable related to the uncertainty of the DAM price	[€]

ν_k^{ID}	Dual variable related to the uncertainty of the price of IDM session k	[€]
$\nu^{\text{SR},\uparrow} / \nu^{\text{SR},\downarrow}$	Dual variable related to the uncertainty of the up/down SRM price	[€]
$\nu_{r(\theta)}^{\text{DA}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) available energy in the DAM	[€]
$\nu_{k,r(\theta)}^{\text{ID}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) available energy in IDM session k	[MWh]
$\nu_{r(\theta)}^{\text{SR}}$	Dual variable related to the uncertainty of the ND-RES r (STU θ) available energy in the SRM	[MWh]

3.1.4 Binary Variables

Symbol	Description	Unit
$u_{c,t}$	Binary variable that is 1 if D-RES c is generating electricity during time period t , and 0 otherwise	[0/1]
$u_{d,p}$	Binary variable to select profile p of demand d	[0/1]
$u_{s,t}$	Binary variable used to prevent the simultaneous charging and discharging of ESS s during time period t	[0/1]
$u_{v,c,t}^{\text{SR}}$	Binary variable used to prevent the simultaneous provision of up and down SR by D-RES c during time period t for calls on condition v by DVPP operator	[0/1]
$u_{v,d,t}^{\text{SR}}$	Binary variable used to prevent the simultaneous provision of up and down SR by demand d during time period t for calls on condition v by DVPP operator	[0/1]
$u_{v,\ell,t}^{\text{SR}}$	Binary variable used to prevent the simultaneous up and down SR flow in line ℓ during time period t for calls on condition v by DVPP operator	[0/1]
$u_{v,r,t}$	Binary variable used to turn off the ND-RES r during time period t for calls on condition v by DVPP operator	[0/1]
$u_{v,r,t}^{\text{SR}}$	Binary variable used to prevent the simultaneous provision of up and down SR by ND-RES r during time period t for calls on condition v by DVPP operator	[0/1]
$u_{v,s,t}^{\text{SR},+} / u_{v,s,t}^{\text{SR},-}$	Binary variable used to prevent the simultaneous provision of up and down SR by ESS s during time period t for calls on condition v by DVPP operator for charging/discharging state	[0/1]
$u_{v,\theta,t}^{\text{SR},+} / u_{v,\theta,t}^{\text{SR},-}$	Binary variable used to prevent the simultaneous provision of up and down SR by STU θ during time period t for calls on condition v by DVPP operator for charging/discharging state	[0/1]
$u_{\theta,t}^+$	Binary variable that is 1 if STU thermal storage θ is charging during time period t	[0/1]

$v_{c,t}^0/v_{c,t}^1$	Binary variable that is 1 if D-RES c is shut down/start up during time period t , and 0 otherwise	[0/1]
$v_{\theta,t}^1$	Binary variable that is 1 if powerblock of STU θ is started up during time period t , and 0 otherwise	[0/1]
$y_{\theta,t,n}$	Auxiliary binary variable in SOS-2 formulation	[0/1]
$\chi_{r(\theta),t}^{\text{DA}}$	Binary variable that is 1 is ND-RES (STU) constraints in the DAM are active, and 0 otherwise	[0/1]
$\chi_{k,r(\theta),t}^{\text{ID}}$	Binary variable that is 1 is ND-RES (STU) constraints in the k -th IDM session are active, and 0 otherwise	[0/1]
$\chi_{r(\theta),t}^{\text{SR}}$	Binary variable that is 1 is ND-RES (STU) constraints in the SRM are active, and 0 otherwise	[0/1]

3.2 DVPP Objective Functions

The objective functions of the DVPP that aims to participate in a sequence of markets, including DAM, SRM and IDMs, are formalized in this section. With this aim, the deterministic formulation of the objective functions presented in Chapter 4 of Deliverable D5.1 for the different market windows is first recalled for the reader's convenience. The robust formulation to cope with uncertainties for all objective functions is then proposed and discussed.

3.2.1 DAM Objective Function

Deterministic Formulation

Equation (3.1) formulates the objective function of a DVPP that participates in the DAM and SRM (see eq. (4.1) of D5.1). The expression considers that the forecasted values of the uncertain parameters, namely the DAM and up/down SRM prices (λ_t^{DA} , $\lambda_t^{\text{SR},\uparrow}$, and $\lambda_t^{\text{SR},\downarrow}$, respectively) are exact, i.e., the actual realizations of such parameters are equal to the values forecasted at the time of preparing the offers to the market operator.

The first three components of the objective function correspond to the sum of the hourly incomes of the power traded in the DAM market and the up/down secondary reserve traded in the SRM. The next two components are subtracted from the previous three components. These two components are the sum over the time horizon of the hourly variable and operation costs of the D-RESs, and the operation and maintenance costs of the ND-RESs of the DVPP. The last two components of the objective function are the costs related to the degradation of the ESSs (if any), and the selection of the daily demand profile.

$$\begin{aligned}
 \max_{\Xi^{\text{DA}}} \sum_{t \in \mathcal{T}} & \left[\underbrace{\lambda_t^{\text{DA}} p_t^{\text{DA}} \Delta t}_{\text{DAM incomes}} + \underbrace{\lambda_t^{\text{SR},\uparrow} r_t^{\text{SR},\uparrow}}_{\text{SRM up regulation incomes}} + \underbrace{\lambda_t^{\text{SR},\downarrow} r_t^{\text{SR},\downarrow}}_{\text{SRM down regulation incomes}} \right. \\
 & \left. - \underbrace{\sum_{c \in \mathcal{C}} (C_c^V p_{c,t}^{\text{DA}} \Delta t + c_{c,t}^0 + c_{c,t}^1)}_{\text{D-RES variable and operation costs}} - \underbrace{\sum_{r \in \mathcal{R}} C_r^M p_{r,t}^{\text{DA}} \Delta t}_{\text{ND-RES variable costs}} \right] \\
 & - \underbrace{\sum_{s \in \mathcal{S}} c_s^{\text{deg}}}_{\text{ESS degradation costs}} - \underbrace{\sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}} C_{d,p} u_{d,p}}_{\text{Demand profile selection costs}}
 \end{aligned} \tag{3.1}$$

Robust Formulation

Two main modifications need to be applied to (3.1) in order to formulate the robust optimization for the DAM and SRM, as indicated in (3.2).

$$\begin{aligned}
 \max_{\Xi^{\text{DA}}} \sum_{t \in \mathcal{T}} & \left[\underbrace{\tilde{\lambda}_t^{\text{DA}} p_t^{\text{DA}} \Delta t + \tilde{\lambda}_t^{\text{SR},\uparrow} r_t^{\text{SR},\uparrow} + \tilde{\lambda}_t^{\text{SR},\downarrow} r_t^{\text{SR},\downarrow}}_{\text{Expected incomes (based on price forecast median)}} \right. \\
 & - \sum_{c \in \mathcal{C}} (C_c^V p_{c,t}^{\text{DA}} \Delta t + c_{c,t}^0 + c_{c,t}^1) - \sum_{r \in \mathcal{R}} C_r^M p_{r,t}^{\text{DA}} \Delta t \Big] \\
 & - \sum_{s \in \mathcal{S}} c_s^{\text{deg}} - \sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}} C_{d,p} u_{d,p} \\
 & - \underbrace{\Gamma^{\text{DA}} \nu^{\text{DA}} - \Gamma^{\text{SR},\uparrow} \nu^{\text{SR},\uparrow} - \Gamma^{\text{SR},\downarrow} \nu^{\text{SR},\downarrow} - \sum_{t \in \mathcal{T}} (\eta_t^{\text{DA}} + \eta_t^{\text{SR},\uparrow} + \eta_t^{\text{SR},\downarrow})}_{\text{Reduction of expected incomes due to price uncertainties}}
 \end{aligned} \tag{3.2}$$

On one hand, the prices are not single, deterministic values, but rather, they can take values within an interval whose bounds that are delimited by the median by adding and subtracting specified deviations, as indicated in (3.3). The incomes of the robust objective function (3.2) are computed using the median value.

$$\lambda_t^{\text{DA}} \in [\tilde{\lambda}_t^{\text{DA}} - \check{\lambda}_t^{\text{DA}}, \tilde{\lambda}_t^{\text{DA}} + \hat{\lambda}_t^{\text{DA}}], \quad \forall t \in \mathcal{T} \tag{3.3a}$$

$$\lambda_t^{\text{SR},\uparrow} \in [\tilde{\lambda}_t^{\text{SR},\uparrow} - \check{\lambda}_t^{\text{SR},\uparrow}, \tilde{\lambda}_t^{\text{SR},\uparrow} + \hat{\lambda}_t^{\text{SR},\uparrow}], \quad \forall t \in \mathcal{T} \tag{3.3b}$$

$$\lambda_t^{\text{SR},\downarrow} \in [\tilde{\lambda}_t^{\text{SR},\downarrow} - \check{\lambda}_t^{\text{SR},\downarrow}, \tilde{\lambda}_t^{\text{SR},\downarrow} + \hat{\lambda}_t^{\text{SR},\downarrow}], \quad \forall t \in \mathcal{T} \tag{3.3c}$$

The second modification of the objective function is indicated in the last line of (3.2) as a reduction of the total expected incomes of the first line of the equation. It represents the worst realization of the price deviations that consequently has the highest impact in the reduction of the total benefit of the optimization problem. Parameters Γ^{DA} , $\Gamma^{\text{SR},\uparrow}$ and $\Gamma^{\text{SR},\downarrow}$, which can take values between 0 and 24 (i.e., the number of periods considered), allow adjusting the *robustness* of the model against uncertainties in the DAM, up regulation of SRM and down regulation of SRM, respectively. When any of the parameters above are equal to 0, no deviations with respect to the median value are considered in the problem, thus effectively becoming a deterministic formulation. When such parameters are equal to 24, the algorithm sets all prices for all periods to one of the extreme values of (3.3). Specifically, the value that worsens the most the objective function (i.e., the upper bound of the interval if the DVPP is buying energy during that period, and the lower bound if selling energy). For any value between 0 and 24, the optimization algorithm will choose the periods for which having the worst realization of uncertain parameters show the highest impact on the objective function. This is illustrated in the examples included in Chapter 5. Note that the user defined parameters Γ^{DA} , $\Gamma^{\text{SR},\uparrow}$ and $\Gamma^{\text{SR},\downarrow}$ can have different values among them, and do not necessarily need to be an integer value. If a rational value is defined, a *fraction* of a period would be selected.

The robust variables ν^{DA} , $\nu^{\text{SR},\uparrow}$ and $\nu^{\text{SR},\downarrow}$ represent the average incomes reduction per uncertain parameter whose deviation is applied to. Finally, the robust variables η_t^{DA} , $\eta_t^{\text{SR},\uparrow}$ and $\eta_t^{\text{SR},\downarrow}$ represent the additional hourly incomes reduction for each price deviation of each market. Additionally, constraints (3.4) must be added to the optimization problem.

Constraints (3.4a) and (3.4b) calculate the volatility of DAM income reduction when the electricity price takes its worst value, i.e., $\tilde{\lambda}_t^{\text{DA}} - \check{\lambda}_t^{\text{DA}}$ if the DVPP is selling energy to the main grid, and $\tilde{\lambda}_t^{\text{DA}} + \check{\lambda}_t^{\text{DA}}$ if buying energy. Constraint (3.4a) sets the incomes deviation for every hour of the DAM. The robust formulation selects the hours where its price deviation affects more to the total incomes. Constraint (3.4b) evaluates the absolute value of the DAM submitted power to cope with positive price deviation, $\hat{\lambda}_t^{\text{DA}}$, and also negative price deviations, $\check{\lambda}_t^{\text{DA}}$. Constraint (3.4c) sets the hourly incomes deviation for the SRM and up secondary reserve power. The robust formulation selects the hours for price deviation that affect the most (negatively) the incomes of the objective function. As the variable $r_t^{\text{SR},\uparrow}$ is positive, there is no need to evaluate the absolute value of this variable. Analogously, the constraint (3.4d) sets the hourly incomes deviation for the SRM and down secondary reserve power. Finally, constraint (3.4e) defines the positive nature of robust dual variables.

$$\nu^{\text{DA}} + \eta_t^{\text{DA}} \geq \hat{\lambda}_t^{\text{DA}} y_t^{\text{DA}}, \quad \forall t \in \mathcal{T} \quad (3.4a)$$

$$-\frac{\hat{\lambda}_t^{\text{DA}}}{\check{\lambda}_t^{\text{DA}}} y_t^{\text{DA}} \leq p_t^{\text{DA}} \Delta t \leq y_t^{\text{DA}}, \quad \forall t \in \mathcal{T} \quad (3.4b)$$

$$\nu^{\text{SR},\uparrow} + \eta_t^{\text{SR},\uparrow} \geq \hat{\lambda}_t^{\text{SR},\uparrow} r_t^{\text{SR},\uparrow}, \quad \forall t \in \mathcal{T} \quad (3.4c)$$

$$\nu^{\text{SR},\downarrow} + \eta_t^{\text{SR},\downarrow} \geq \hat{\lambda}_t^{\text{SR},\downarrow} r_t^{\text{SR},\downarrow}, \quad \forall t \in \mathcal{T} \quad (3.4d)$$

$$\nu^{\text{DA}}, \nu^{\text{SR},\uparrow}, \nu^{\text{SR},\downarrow}, \eta_t^{\text{DA}}, \eta_t^{\text{SR},\uparrow}, \eta_t^{\text{SR},\downarrow}, y_t^{\text{DA}} \geq 0, \quad \forall t \in \mathcal{T} \quad (3.4e)$$

3.2.2 SRM Objective Function

In the DAM problem discussed in Section 3.2.1, the viability of participating in the secondary reserve market is also considered. However, when the offer/bid is submitted to the market operator, only the energy to be traded in the DAM is submitted (see Section 2.2 of Deliverable D5.1 for more details on the market structure).

Assuming, without loss of generality, that the DVPP is a net energy seller, then the energy that the DVPP had available (at least from the forecast) and was not offered in the DAM, is considered as *reserved* for the SRM. In Spain, the SRM closure time is almost simultaneous with the first IDM. Since this time is also closer to the first power delivery period, it is expected that the forecasts of the uncertain data, if updated with respect to those available when the DAM problem was solved, are more accurate. Moreover, since the first IDM session might have higher prices than the SRM, the DVPP might consider the total or partial allocation of the reserve in the IDM. This was formally formulated in eq. (4.2) of D5.1, and is recalled below in (3.5) for completeness. The result of this deterministic optimization problem will be then submitted for participating in both the SRM and first IDM.

$$\begin{aligned}
 \max_{\Xi^{\text{SR}}} \sum_{t \in \mathcal{T}} & \left[\underbrace{\lambda_t^{\text{SR},\uparrow} r_t^{\text{SR},\uparrow} + \lambda_t^{\text{SR},\downarrow} r_t^{\text{SR},\downarrow} + \lambda_{(k=1),t}^{\text{ID}} p_{(k=1),t}^{\text{ID}} \Delta t}_{\text{Expected incomes from SRM and the first IDM}} \right. \\
 & \left. - \sum_{c \in \mathcal{C}} \left(C_c^V p_{(k=1),c,t}^{\text{ID}} \Delta t + c_{c,t}^0 + c_{c,t}^1 \right) - \sum_{r \in \mathcal{R}} \left(C_r^M p_{(k=1),r,t}^{\text{ID}} \Delta t \right) \right] - \sum_{s \in \mathcal{S}} c_s^{\text{deg}}
 \end{aligned} \tag{3.5}$$

Robust Formulation for SRM Objective Function

The robust formulation of the deterministic problem above is presented in (3.6). The incomes reduction comes from the volatility of up/down SRM price, and the first IDM price. The robustness parametrization is defined at both markets by the corresponding parameters $\Gamma^{\text{SR},\uparrow}$, $\Gamma^{\text{SR},\downarrow}$ for the SRM, and $\Gamma_{(k=1)}^{\text{ID}}$ for the first IDM.

The robust dual variables $\nu^{\text{SR},\uparrow}$, $\nu^{\text{SR},\downarrow}$ and $\nu_{(k=1)}^{\text{ID}}$ represent the average benefit reduction per uncertain parameter whose deviation is applied to each market. The robust dual variables $\eta_t^{\text{SR},\uparrow}$, $\eta_t^{\text{SR},\downarrow}$ and $\eta_{(k=1),t}^{\text{ID}}$ represent the additional hourly benefit reduction for each price deviation of each market.

$$\begin{aligned}
 \max_{\Xi^{\text{SR}}} \sum_{t \in \mathcal{T}} & \left[\underbrace{\tilde{\lambda}_t^{\text{SR},\uparrow} r_t^{\text{SR},\uparrow} + \tilde{\lambda}_t^{\text{SR},\downarrow} r_t^{\text{SR},\downarrow} + \tilde{\lambda}_{(k=1),t}^{\text{ID}} p_{(k=1),t}^{\text{ID}} \Delta t}_{\text{Expected incomes (based on price forecast median)}} \right. \\
 & \left. - \sum_{c \in \mathcal{C}} \left(C_c^V p_{(k=1),c,t}^{\text{ID}} \Delta t + c_{c,t}^0 + c_{c,t}^1 \right) - \sum_{r \in \mathcal{R}} \left(C_r^M p_{(k=1),r,t}^{\text{ID}} \Delta t \right) \right] - \sum_{s \in \mathcal{S}} c_s^{\text{deg}} \\
 & - \Gamma^{\text{SR},\uparrow} \nu^{\text{SR},\uparrow} - \Gamma^{\text{SR},\downarrow} \nu^{\text{SR},\downarrow} - \Gamma_{(k=1)}^{\text{ID}} \nu_{(k=1)}^{\text{ID}} - \sum_{t \in \mathcal{T}} \left(\eta_t^{\text{SR},\uparrow} + \eta_t^{\text{SR},\downarrow} + \eta_{(k=1),t}^{\text{ID}} \right)
 \end{aligned} \tag{3.6}$$

Additionally, the following constraints must be added to the optimization problem.

Constraints (3.7) set a flexible robust scenario of up/down SRM and IDM#1 electricity prices to cope with the volatility of income reduction in the SRM objective function. Constraints (3.7a)-(3.7c) set the corresponding benefit reductions of the SRM objective function (3.6). The first two constraints correspond to the SRM and the third constraint to the IDM#1.

Since, when considering robustness in the SRM, the price deviation of up/down SRM prices is the one that reduces the profit of the reserve provided, the deviation is thus always the *negative* one. However, to implement the flexible robustness for the IDM#1, the price deviation should be the one that sets a resulting price of $\tilde{\lambda}_{(k=1),t}^{\text{ID}} - \tilde{\lambda}_{(k=1),t}^{\text{ID}}$ (i.e., negative deviation) when the DVPP is selling energy to the IDM#1. On the other hand, the resulting price at the IDM#1 should be $\tilde{\lambda}_{(k=1),t}^{\text{ID}} + \tilde{\lambda}_{(k=1),t}^{\text{ID}}$ (i.e., positive deviation) when the DVPP is buying energy.

$$\nu^{\text{SR},\uparrow} + \eta_t^{\text{SR},\uparrow} \geq \hat{\lambda}_t^{\text{SR},\uparrow} r_t^{\text{SR},\uparrow}, \quad \forall t \in \mathcal{T} \quad (3.7a)$$

$$\nu^{\text{SR},\downarrow} + \eta_t^{\text{SR},\downarrow} \geq \hat{\lambda}_t^{\text{SR},\downarrow} r_t^{\text{SR},\downarrow}, \quad \forall t \in \mathcal{T} \quad (3.7b)$$

$$\nu_{(k=1)}^{\text{ID}} + \eta_{(k=1),t}^{\text{ID}} \geq \hat{\lambda}_{(k=1),t}^{\text{ID}} y_{(k=1),t}^{\text{ID}}, \quad \forall t \in \mathcal{T} \quad (3.7c)$$

$$-\frac{\hat{\lambda}_{(k=1),t}^{\text{ID}}}{\hat{\lambda}_{(k=1),t}^{\text{ID}}} y_{(k=1),t}^{\text{ID}} \leq p_{(k=1),t}^{\text{ID}} \Delta t \leq y_{(k=1),t}^{\text{ID}}, \quad \forall t \in \mathcal{T} \quad (3.7d)$$

$$\nu^{\text{SR},\uparrow}, \nu^{\text{SR},\downarrow}, \nu_{(k=1)}^{\text{ID}}, \eta_t^{\text{SR},\uparrow}, \eta_t^{\text{SR},\downarrow}, \eta_{(k=1),t}^{\text{ID}}, y_{(k=1),t}^{\text{ID}} \geq 0, \quad \forall t \in \mathcal{T} \quad (3.7e)$$

3.2.3 IDMs Objective Function

The objective function of all IDM is formulated in a deterministic way in (3.8) (see Section 4.2.3 of Deliverable D5.1). All IDM prices and operation and maintenance costs are taken into account for D-RESs and ND-RESs of the DVPP.

$$\begin{aligned} \max_{\Xi^{\text{ID}}} \sum_{t \geq \tau} \left[\lambda_{k,t}^{\text{ID}} p_{k,t}^{\text{ID}} \Delta t - \sum_{c \in \mathcal{C}} (C_c^V p_{k,c,t}^{\text{ID}} \Delta t + c_{k,c,t}^0 + c_{k,c,t}^1) \right. \\ \left. - \sum_{r \in \mathcal{R}} (C_r^M p_{k,r,t}^{\text{ID}} \Delta t) \right] - \sum_{s \in \mathcal{S}} c_s^{\text{deg}}, \quad \forall k \in \mathcal{K} \end{aligned} \quad (3.8)$$

Robust Formulation for IDMs Objective Function

The robustness income reduction in the IDMs objective function (3.9) comes from IDMs prices volatility. The uncertainty budget Γ_k^{ID} should be assigned according to the number of each IDM periods as each IDM has different time horizon. The dual variable ν_k^{ID} represents the average income reduction per period where the price deviation is applied to, whereas the dual variable $\eta_{k,t}^{\text{ID}}$ represents the additional income reduction per each period at each IDM.

$$\begin{aligned} \max_{\Xi^{\text{ID}}} \sum_{t \geq \tau} \left[\tilde{\lambda}_{k,t}^{\text{ID}} p_{k,t}^{\text{ID}} \Delta t - \sum_{c \in \mathcal{C}} (C_c^V p_{k,c,t}^{\text{ID}} \Delta t + c_{k,c,t}^0 + c_{k,c,t}^1) \right. \\ \left. - \sum_{r \in \mathcal{R}} (C_r^M p_{k,r,t}^{\text{ID}} \Delta t) \right] - \sum_{s \in \mathcal{S}} c_s^{\text{deg}} - \Gamma_k^{\text{ID}} \nu_k^{\text{ID}} - \sum_{t \geq \tau} \eta_{k,t}^{\text{ID}}, \quad \forall k \in \mathcal{K} \end{aligned} \quad (3.9)$$

Constraints (3.10) must be added to the optimization problem, which calculate the income reduction arises from worst case IDM electricity prices in the IDM objective function (3.9). The price deviations will be those that reduce the most the expected incomes. As for the previous case in Section 3.2.2, the price deviation of each period should be negative and the resulting price would be $\tilde{\lambda}_{k,t}^{\text{ID}} - \hat{\lambda}_{k,t}^{\text{ID}}$ when the DVPP sells energy in that period. Alternatively, the price deviation of each period should be positive and the resulting price would be $\tilde{\lambda}_{k,t}^{\text{ID}} + \hat{\lambda}_{k,t}^{\text{ID}}$ if the DVPP is a net energy buyer in that period.

$$\nu_k^{\text{ID}} + \eta_{k,t}^{\text{ID}} \geq \hat{\lambda}_{k,t}^{\text{ID}} y_{k,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall t \geq \tau \quad (3.10a)$$

$$-\frac{\hat{\lambda}_{k,t}^{\text{ID}}}{\hat{\lambda}_{k,t}^{\text{ID}}} y_{k,t}^{\text{ID}} \leq p_{k,t}^{\text{ID}} \Delta t \leq y_{k,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall t \geq \tau \quad (3.10b)$$

$$\nu_k^{\text{ID}}, \eta_{k,t}^{\text{ID}}, y_{k,t}^{\text{ID}} \geq 0, \quad \forall k \in \mathcal{K}, \forall t \geq \tau \quad (3.10c)$$

3.3 Constraints

This section discusses the constraints of the robust optimization algorithm proposed in this document. The constraints for the deterministic formulation of the problem, presented in Chapter 4 of Deliverable D5.1, that are common in both formulations are not included in this deliverable. Instead, only modifications and additions with respect to the formulation of D5.1 are considered.

3.3.1 DAM Power Traded Constraints

The formulation of this set of constraints comprise equations (4.15)-(4.21) of Chapter 4 of Deliverable D5.1. This set of equations has been expanded with two additional expressions in order to tailor such a set to the Spanish case which is considered for the illustrative examples presented in Chapter 5, as follows.

The amount of requested down reserve by the Spanish system operator is a proportion of up reserve for each time period, which is modeled by (3.11a). Constraint (3.11b) sets the limit of up reserve traded in the market according to a share of total power capacity of the DVPP, defined by the user-defined parameter κ . Note that, if $\kappa = 0$, then the DVPP will only participate in the DAM, as no power would be allocated in the SRM.

$$r_t^{\text{SR},\uparrow} = \varrho_t r_t^{\text{SR},\downarrow}, \quad \forall t \in \mathcal{T} \quad (3.11a)$$

$$r_t^{\text{SR},\uparrow} \leq \kappa \left(\sum_{c \in \mathcal{C}} \bar{P}_c + \sum_{r \in \mathcal{R}} \bar{P}_{r,t} + \sum_{\theta \in \Theta} \bar{P}_\theta + \sum_{s \in \mathcal{S}} \bar{P}_s^- \right), \quad \forall t \in \mathcal{T} \quad (3.11b)$$

$$r_t^{\text{SR},\uparrow}, r_t^{\text{SR},\downarrow} \geq 0, \quad \forall t \in \mathcal{T} \quad (3.11c)$$

3.3.2 SRM Power Traded Constraints

The formulation of this set of constraints comprise equations (4.18), (4.19) and (4.22)-(4.26) of Chapter 4 of Deliverable D5.1. This set of equations has been expanded with constraints (3.11a) and (3.11b) above in order to tailor such a set to the Spanish case.

3.3.3 Robust Formulation of ND-RES Constraints in the DAM

The ND-RES energy input robustness formulation in the DAM is presented in (3.12). Constraint (3.12a) limits the output power of ND-RESs considering the median and negative deviation of input power. The minimum power provided by the ND-RES is assigned by (3.12b). The negative deviation of ND-RESs input power is upper bounded by (3.12c). Constraint (3.12d) assigns the minimum value for power reduction in each time period according to the uncertainty budget Γ_r^{DA} which is predefined by DVPP operator. Unlike the uncertainty budgets already defined (Γ^{DA} , $\Gamma^{\text{SR},\uparrow}$, $\Gamma^{\text{SR},\downarrow}$, and Γ_k^{ID}), which account for the worst price realizations from the objective function point of view, the ND-RES energy uncertainty budget Γ_r^{DA} represents the *number of periods* with the highest uncertain variations in the negative range of uncertainty (i.e., with the highest reduction of available power in the ND-RES).

The binary variable $\chi_{r,t}^{\text{DA}}$ sets the active or non-active status of each time period for completion of the robustness budget Γ_r^{DA} predefined. This variable is set to 1 when the available energy deviation of the DAM occurs at the hour t in the DAM. The DVPP operator can adopt more conservative strategies by selecting higher value for the integer parameter Γ_r^{DA} for each ND-RES. The dual variables related to input power robustness reduction, ν_r^{DA} and $\eta_{r,t}^{\text{DA}}$, in (3.12d) are bounded by (3.12e)-(3.12f) based on the active or non-active status of the period to complete the robustness budget. Constraint (3.12g) limits the number of periods that are affected by considering the robust strategy. For instance, if $\Gamma_r^{\text{DA}} = 3$, the ND-RES power reduces to its worst value in 3 time periods. The nature of input power deviation and dual robust variables is defined in (3.12h). Constraint (3.12i) shows the nature of robust completeness binary variable $\chi_{r,t}^{\text{DA}}$. Finally, constraints (3.12j)-(3.12l) correspond to equations (4.80)–(4.82) of Deliverable D5.1, and are included here for the sake of completeness.

$$p_{r,t}^{\text{DA}} + r_{v,r,t}^{\text{SR},\uparrow} \leq \tilde{P}_{r,t}^{\text{DA}} - y_{r,t}^{\text{DA}}, \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12a)$$

$$\underline{P}_{r,t} \leq p_{r,t} - r_{v,r,t}^{\text{SR},\downarrow}, \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12b)$$

$$y_{r,t}^{\text{DA}} \leq \check{P}_{r,t}^{\text{DA}}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12c)$$

$$y_{r,t}^{\text{DA}} \geq \nu_r^{\text{DA}} + \eta_{r,t}^{\text{DA}} - \max_{tt} \left(\check{P}_{r,tt}^{\text{DA}} \right) (1 - \chi_{r,t}^{\text{DA}}), \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12d)$$

$$\nu_r^{\text{DA}} + \eta_{r,t}^{\text{DA}} \geq \check{P}_{r,t}^{\text{DA}}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12e)$$

$$\varepsilon \chi_{r,t}^{\text{DA}} \leq \eta_{r,t}^{\text{DA}} \leq \max_{tt} (\check{P}_{r,tt}^{\text{DA}}) \chi_{r,t}^{\text{DA}}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12f)$$

$$\sum_{t \in \mathcal{T}} \chi_{r,t}^{\text{DA}} \geq \Gamma_r^{\text{DA}}, \quad \forall r \in \mathcal{R} \quad (3.12g)$$

$$\nu_r^{\text{DA}}, \eta_{r,t}^{\text{DA}}, y_{r,t}^{\text{DA}} \geq 0, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12h)$$

$$\chi_{r,t}^{\text{DA}} \in \{0, 1\}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12i)$$

$$r_{v,r,t}^{\text{SR},\uparrow} \leq T^{\text{SR}} \bar{R}_r^{\text{SR}} u_{v,r,t}^{\text{SR}}, \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12j)$$

$$r_{v,r,t}^{\text{SR},\downarrow} \leq T^{\text{SR}} \underline{R}_r^{\text{SR}} (1 - u_{v,r,t}^{\text{SR}}), \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12k)$$

$$u_{v,r,t}^{\text{SR}} \in \{0, 1\}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.12l)$$

3.3.4 Robust Formulation of ND-RES Constraints in the SRM

The ND-RES energy robustness formulation in the SRM is formulated in (3.13). Constraint (3.13a) limits the submitted power of ND-RES in the SRM considering the robustness effect. The DAM power previously cleared in that market is included in this constraint as a fixed parameter, $p_{r,t}^*$. The SRM and IDM#1 power variables, $r_{v,r,t}^{\text{SR},\uparrow}$, $r_{v,r,t}^{\text{SR},\downarrow}$ and $p_{(k=1),r,t}^{\text{ID}}$ are the ones to optimize in this model. The robustness constraints (3.13b)- (3.13l) are defined similarly to Section 3.3.3. In this case the robustness budget defined by the user in this model is Γ_r^{SR} , and the activation robust completeness binary variable is $\chi_{r,t}^{\text{SR}}$. This variable is set to 1 when the SRM price deviation of the ND-RES r occurs at the hour t in the SRM.

$$p_{r,t}^* + r_{v,r,t}^{\text{SR},\uparrow} + p_{(k=1),r,t}^{\text{ID}} \leq \tilde{P}_{r,t}^{\text{SR}} - y_{r,t}^{\text{SR}}, \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13a)$$

$$\underline{P}_{r,t} \leq p_{r,t}^* - r_{v,r,t}^{\text{SR},\downarrow} + p_{(k=1),r,t}^{\text{ID}}, \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13b)$$

$$y_{r,t}^{\text{SR}} \leq \check{P}_{r,t}^{\text{SR}}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13c)$$

$$y_{r,t}^{\text{SR}} \geq \nu_r^{\text{SR}} + \eta_{r,t}^{\text{SR}} - \max_{tt} \left(\check{P}_{r,tt}^{\text{SR}} \right) (1 - \chi_{r,t}^{\text{SR}}), \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13d)$$

$$\nu_r^{\text{SR}} + \eta_{r,t}^{\text{SR}} \geq \check{P}_{r,t}^{\text{SR}}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13e)$$

$$\varepsilon \chi_{r,t}^{\text{SR}} \leq \eta_{r,t}^{\text{SR}} \leq \max_{tt} (\check{P}_{r,tt}^{\text{SR}}) \chi_{r,t}^{\text{SR}}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13f)$$

$$\sum_{t \in \mathcal{T}} \chi_{r,t}^{\text{SR}} \geq \Gamma_r^{\text{SR}}, \quad \forall r \in \mathcal{R} \quad (3.13g)$$

$$\nu_r^{\text{SR}}, \eta_{r,t}^{\text{SR}}, y_{r,t}^{\text{SR}} \geq 0, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13h)$$

$$\chi_{r,t}^{\text{SR}} \in \{0, 1\}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13i)$$

$$r_{v,r,t}^{\text{SR},\uparrow} \leq T^{\text{SR}} \bar{R}_r^{\text{SR}} u_{v,r,t}^{\text{SR}}, \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13j)$$

$$r_{v,r,t}^{\text{SR},\downarrow} \leq T^{\text{SR}} \underline{R}_r^{\text{SR}} (1 - u_{v,r,t}^{\text{SR}}), \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13k)$$

$$u_{v,r,t}^{\text{SR}} \in \{0, 1\}, \quad \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (3.13l)$$

3.3.5 Robust Formulation of ND-RES Constraints in the IDM

The ND-RES energy robustness formulation in the IDMs is formulated in (3.14). The output power of ND-RES in each IDM session is limited according to constraints (3.14a) and (3.14b) considering the fixed power and reserve from previous markets. The robustness constraints (3.14c)- (3.14i) are defined for each IDM session similar to DAM formulation. In this model the DAM and SRM power outputs are fixed by previous models. In addition, the IDM variables previous to the one that is in this model are also fixed. In this model the robustness budget $\Gamma_{k,r}^{\text{ID}}$ is completed using the activation robust completeness variables for the specific k IDM, $\chi_{k,r,t}^{\text{ID}}$. This variable is set to 1 when the power input of the ND-RES r has a reduction at the hour t in the IDM# k .

$$p_{r,t}^* + \max \left\{ r_{(v=1),r,t}^{*,\text{SR},\uparrow}, r_{(v=2),r,t}^{*,\text{SR},\uparrow} \right\} + \sum_{k=1}^{k-1} p_{k,r,t}^{*\text{ID}} + p_{k,r,t}^{\text{ID}} \leq \tilde{P}_{k,r,t}^{\text{ID}} - y_{k,r,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14a)$$

$$\underline{P}_{r,t} \leq p_{r,t}^* - \max \left\{ r_{(v=1),r,t}^{*,\text{SR},\downarrow}, r_{(v=2),r,t}^{*,\text{SR},\downarrow} \right\} + \sum_{k=1}^{k-1} p_{k,r,t}^{*\text{ID}} + p_{k,r,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14b)$$

$$y_{k,r,t}^{\text{ID}} \leq \tilde{P}_{k,r,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14c)$$

$$y_{k,r,t}^{\text{ID}} \geq \nu_{k,r}^{\text{ID}} + \eta_{k,r,t}^{\text{ID}} - \max_{tt} \left(\tilde{P}_{k,r,tt}^{\text{ID}} \right) (1 - \chi_{k,r,t}^{\text{ID}}), \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14d)$$

$$\nu_{k,r}^{\text{ID}} + \eta_{k,r,t}^{\text{ID}} \geq \tilde{P}_{k,r,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14e)$$

$$\varepsilon \chi_{k,r,t}^{\text{ID}} \leq \eta_{r,t}^{\text{ID}} \leq \max_{tt} (\tilde{P}_{k,r,tt}^{\text{ID}}) \chi_{k,r,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14f)$$

$$\sum_{t \geq \tau} \chi_{k,r,t}^{\text{ID}} \geq \Gamma_{k,r}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R} \quad (3.14g)$$

$$\nu_{k,r}^{\text{ID}}, \eta_{k,r,t}^{\text{ID}}, y_{k,r,t}^{\text{ID}} \geq 0, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14h)$$

$$\chi_{k,r,t}^{\text{ID}} \in \{0, 1\}, \quad \forall k \in \mathcal{K}, \forall r \in \mathcal{R}, \forall t \geq \tau \quad (3.14i)$$

3.3.6 Robust Formulation of STU Constraints in the DAM

The solar field energy robustness formulation in the DAM is presented in (3.15). The output solar field energy is limited by considering the effect of solar irradiation volatility. Robustness constraints (3.15d)-(3.15h) are defined similarly to the ND-RESs robust formulation in the DAM in Section 3.3.3. In this model, the robustness budget $\Gamma_{\theta}^{\text{DA}}$ is completed using the activation robust completeness variables, $\chi_{\theta,t}^{\text{DA}}$. This variable is set to 1 when the power input of the STU θ has a solar energy reduction at the hour t in the DAM. The maximum reduction of the solar energy, represented by $y_{\theta,t}^{\text{DA}}$, is the deviation $\check{P}_{\theta,t}^{\text{DA}}$ as the constraint (3.15b) shows. Constraints (3.15c) and (3.15d) set that if the robustness activation, $\chi_{\theta,t}^{\text{DA}}$ is equal to 1, then the energy deviation is equal to the maximum reduction. The constraint (3.15f) sets that the activation robust completeness variables, $\chi_{\theta,t}^{\text{DA}}$, should sum at least the robustness budget of DAM for the STU. Note that the volatility of the STU input energy affects differently than the ND-RES volatility, as the input energy is not converted directly into electric power as it occurs at ND-RES (see Section 3.3.3), but into thermal as an intermediate process.

$$p_{\theta,t}^{\text{SF}} \leq \tilde{P}_{\theta,t}^{\text{DA}} - y_{\theta,t}^{\text{DA}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.15a)$$

$$y_{\theta,t}^{\text{DA}} \leq \check{P}_{\theta,t}^{\text{DA}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.15b)$$

$$y_{\theta,t}^{\text{DA}} \geq \nu_{\theta}^{\text{DA}} + \eta_{\theta,t}^{\text{DA}} - \max_{tt} \left(\check{P}_{\theta,tt}^{\text{DA}} \right) (1 - \chi_{\theta,t}^{\text{DA}}), \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.15c)$$

$$\nu_{\theta}^{\text{DA}} + \eta_{\theta,t}^{\text{DA}} \geq \check{P}_{\theta,t}^{\text{DA}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.15d)$$

$$\varepsilon \chi_{\theta,t}^{\text{DA}} \leq \eta_{\theta,t}^{\text{DA}} \leq \max_{tt} (\check{P}_{\theta,tt}^{\text{DA}}) \chi_{\theta,t}^{\text{DA}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.15e)$$

$$\sum_{t \in \mathcal{T}} \chi_{\theta,t}^{\text{DA}} \geq \Gamma_{\theta}^{\text{DA}}, \quad \forall \theta \in \Theta \quad (3.15f)$$

$$\nu_{\theta}^{\text{DA}}, \eta_{\theta,t}^{\text{DA}}, y_{\theta,t}^{\text{DA}} \geq 0, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.15g)$$

$$\chi_{\theta,t}^{\text{DA}} \in \{0, 1\}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.15h)$$

3.3.7 Robust Formulation of STU Constraints in the SRM

The solar field energy robustness formulation in the SRM is constrained by (3.16), and is defined similar to DAM robustness constraints.

$$p_{\theta,t}^{\text{SF}} \leq \tilde{P}_{\theta,t}^{\text{SR}} - y_{\theta,t}^{\text{SR}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.16a)$$

$$y_{\theta,t}^{\text{SR}} \leq \check{P}_{\theta,t}^{\text{SR}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.16b)$$

$$y_{\theta,t}^{\text{SR}} \geq \nu_{\theta}^{\text{SR}} + \eta_{\theta,t}^{\text{SR}} - \max_{tt} \left(\check{P}_{\theta,tt}^{\text{SR}} \right) (1 - \chi_{\theta,t}^{\text{SR}}), \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.16c)$$

$$\nu_{\theta}^{\text{SR}} + \eta_{\theta,t}^{\text{SR}} \geq \check{P}_{\theta,t}^{\text{SR}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.16d)$$

$$\varepsilon \chi_{\theta,t}^{\text{SR}} \leq \eta_{\theta,t}^{\text{SR}} \leq \max_{tt} (\check{P}_{\theta,tt}^{\text{SR}}) \chi_{\theta,t}^{\text{SR}}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.16e)$$

$$\sum_{t \in \mathcal{T}} \chi_{\theta,t}^{\text{SR}} \geq \Gamma_{\theta}^{\text{SR}}, \quad \forall \theta \in \Theta \quad (3.16f)$$

$$\nu_{\theta}^{\text{SR}}, \eta_{\theta,t}^{\text{SR}}, y_{\theta,t}^{\text{SR}} \geq 0, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.16g)$$

$$\chi_{\theta,t}^{\text{SR}} \in \{0, 1\}, \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (3.16h)$$

3.3.8 Robust Formulation of STU Constraints in the IDM

The solar field energy robustness formulation in the IDM is constrained by (3.17), and is defined similar to DAM robustness constraints.

$$p_{k,\theta,t}^{\text{SF}} \leq \tilde{P}_{k,\theta,t}^{\text{ID}} - y_{k,\theta,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17a)$$

$$y_{k,\theta,t}^{\text{ID}} \leq \check{P}_{k,\theta,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17b)$$

$$y_{k,\theta,t}^{\text{ID}} \geq \nu_{k,\theta}^{\text{ID}} + \eta_{k,\theta,t}^{\text{ID}} - \max \left(\check{P}_{k,\theta,tt \in \mathcal{T}}^{\text{ID}} \right) (1 - \chi_{k,\theta,t}^{\text{ID}}), \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17c)$$

$$\nu_{k,\theta}^{\text{ID}} + \eta_{k,\theta,t}^{\text{ID}} \geq \check{P}_{k,\theta,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17d)$$

$$\varepsilon \chi_{k,\theta,t}^{\text{ID}} \leq \eta_{k,\theta,t}^{\text{ID}} \leq \max(\check{P}_{k,\theta,tt \in \mathcal{T}}^{\text{ID}}) \chi_{k,\theta,t}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17e)$$

$$\sum_{t \in \mathcal{T}} \chi_{k,\theta,t}^{\text{ID}} \geq \Gamma_{k,\theta}^{\text{ID}}, \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17f)$$

$$\nu_{k,\theta}^{\text{ID}}, \eta_{k,\theta,t}^{\text{ID}}, y_{k,\theta,t}^{\text{ID}} \geq 0, \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17g)$$

$$\chi_{k,\theta,t}^{\text{ID}} \in \{0, 1\}, \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta, \forall t \geq \tau \quad (3.17h)$$

3.4 Summary of Formulation of Robust Optimization of a DVPP Participating in Electricity Markets

This section summarizes the sets of equations to be implemented for the optimal robust participation of a DVPP in energy and reserve markets.

Table 3-5 Final Formulation - Simultaneous DAM and SRM Robust Participation

Type	D5.1 Eq. Reference	D5.2 Eq. Reference
Objective Function		(3.2)
Price Robustness Constraints		(3.4)
Balancing Constraints	(4.4)–(4.9)	
Power Traded Constraints	(4.15)–(4.21)	(3.11)
D-RES Constraints	(4.37)–(4.55)	
ND-RES Constraints		(3.12)
Flexible Demand Constraints	(4.88)–(4.98)	
ESS Constraints	(4.110)–(4.131)	
STU Constraints	(4.146)–(4.176); (4.201)–(4.206)	(3.15)
Network Constraints	(4.33)–(4.36)	

Table 3-6 Final Formulation - Simultaneous SRM and IDM#1 Robust Participation

Type	D5.1 Eq. Reference	D5.2 Eq. Reference
Objective Function		(3.6)
Price Robustness Constraints		(3.7)
Balancing Constraints	(4.6)–(4.11)	
Power Traded Constraints	(4.18)–(4.19); (4.22)–(4.26)	(3.11)
D-RES Constraints	(4.37)–(4.38); (4.43)–(4.59)	
ND-RES Constraints		(3.13)
Flexible Demand Constraints	(4.94)–(4.95); (4.97)–(4.103)	
ESS Constraints ¹	(4.110)–(4.117); (4.119)–(4.132)	
STU Constraints	(4.146)–(4.160); (4.162)–(4.177); (4.201)–(4.206)	(3.16)
Network Constraints	(4.33)–(4.36)	

¹ The ESS active power in the DAM, $p_{s,t}^*$, is a fixed parameter, given by solving the DAM+SRM problem.

Table 3-7 Final Formulation - IDM Robust Participation

Type	D5.1 Eq. Reference	D5.2 Eq. Reference
Objective Function		(3.9)
Price Robustness Constraints		(3.10)
Balancing Constraints	(4.13)–(4.14)	
Power Traded Constraints	(4.28)–(4.32)	
D-RES Constraints	(4.61)–(4.77)	
ND-RES Constraints		(3.14)
Flexible Demand Constraints	(4.105)–(4.109)	
ESS Constraints ²	(4.134)–(4.144)	
STU Constraints	(4.180)–(4.206)	(3.17)
Network Constraints ²	(4.33)–(4.36)	

² Index k needs to be added to the variables in this set of equations

4 DVPP Optimal Operation under Uncertainty User Manual

In this chapter, the user manual for DVPP participation in different electricity markets, namely DAM, SRM and IDMs, is presented. The user can define the parameters of DVPP units, the DVPP subnetwork data, and the forecast data of uncertain parameters in an Excel file with multiple structured sheets. All the models for deterministic and robust optimization are implemented in General Algebraic Modeling System (GAMS). The GAMS code acts as a *black box* for the user, as no interaction with it is required. After executing the optimization problem for a specific market, the results are written in the same Excel file. Moreover, the interconnections between different markets are duly considered. Subsequent market sessions require the results from previous ones, thus creating this interdependence. However, the intermediate data is used for subsequent markets optimization, can be modified by the user if there is a need for adjustment in the Excel file.

A summary of the information contained in the remainder of this Section is provided in Table 4-1 below.

Table 4-1 Summary of User Manual Contents

Section Number & Title	Description
Section 4.1 – Tool Description and Capabilities	The user becomes familiar with the different elements of the tool, the capabilities of the tool for running optimization problems in different electricity markets, and how to use the tool to obtain the desired results.
Section 4.2 – Input Data	The user becomes familiar with the different input Excel sheets which are used to define the DVPP components and structure, the DVPP subnetwork, the data from forecast centers, the data from transmission system operators, and electricity markets data.
Section 4.3 – Intermediate Data	Data from previous markets optimization or realistic results from previous markets need to be determined to successfully run the optimization problem. The user becomes familiar with this kind of data and how to properly define them in the Excel file.
Section 4.4 – Output Data	The user becomes familiar with each Excel sheet that is used to display the results obtained from running the optimization problem for different electricity markets.

4.1 Tool Description and Capabilities

The tool developed in this Task allows the user to parametrize the DVPP participation in different energy and reserve markets to maximize the benefit of DVPP. The model implemented in the GAMS black box is *general*, meaning that the user can define any DVPP configuration (units and distribution), as well as any market participation, from the Excel file. The units that can be defined include D-RES, ND-RES, STU, ESS, and flexible demands. Multiple units of each kind can be defined. The input data for DVPP units, DVPP sub-network data, and forecast data including different electricity market prices as well as ND-RES and STU energy forecasts need to be defined in the Excel file. Multiple text files (also inaccessible to the user) are provided to *communicate* Excel and GAMS. After executing the optimization problem, the results for each market will be written in specific Excel sheets that can be read by the user. Moreover, intermediate Excel sheets are provided to consider the interdependence between different markets. The intermediate Excel sheets provide some input parameters for running subsequent markets. However, the data in these Excel sheets can be modified by user if desired.

A simplified representation of the data structure of the proposed tool is depicted in Fig. 4-1.

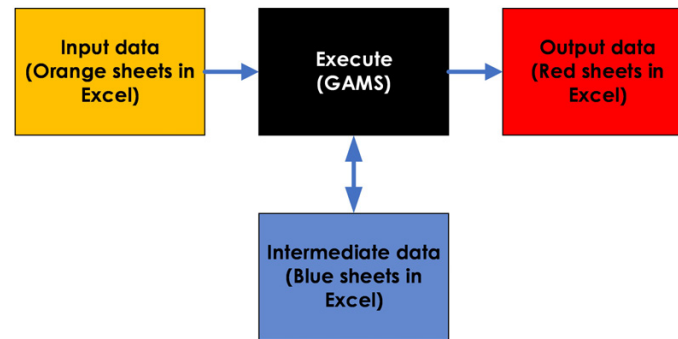


Figure 4-1 Simplified data structure of the tool developed.

In Fig. 4-2, the process of running the optimization algorithm for different electricity markets is shown. For executing the DAM, apart from defining all input parameters related to the DVPP and the uncertain profile forecasts, the user needs to set the parameter `sMarket=-1` in the Excel sheet `Global_params`. The results will be the DAM schedule, as well as the DVPP offers in the DAM and SRM. Such SRM offers can be then updated if solving the SRM+IDM#1, for which the forecast data is expected to be more accurate.

At this stage, the intermediate (blue) Excel sheets will be updated. For running the SRM problem, the user needs to set the parameter `sMarket=0`. The user can also change the Intermediate data sheets if necessary. The results will be an updated schedule for DVPP units, as well as the SRM and IDM#1 offers.

Subsequently, the IDM#1 offers can be revised if updated forecasts are received before the market closure time. To run the IDM#1 problem and obtain its updated schedule, it is required to set `sMarket=1`, and Intermediate data sheets need to be properly assigned.

Note that, if the DVPP operator decides to not participate in the SRM, the IDMs problem can still be solved after DAM execution. The procedure of running other IDMs are similar to IDM#1. The user just needs to change sMarket parameter from 2 through 7 and update Intermediate Excel sheets accordingly.

At the moment of writing this document, the user needs to execute the GAMS optimization algorithm through an auxiliary file with .gdx format, which serves as interface between Excel and GAMS. In future stages of development of the tool, the user will be able to execute the optimization algorithm from the Excel file, without the need for the .gdx auxiliary file.

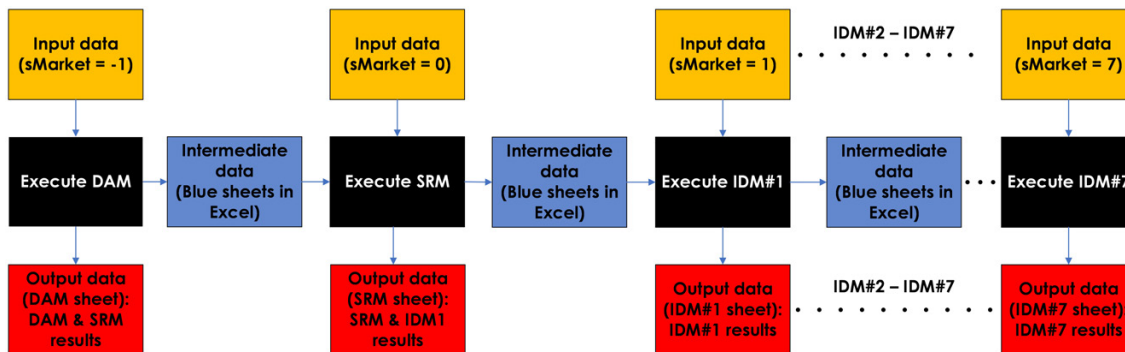


Figure 4-2 Functionality of the tool for DVPP optimal operation under uncertainty

4.2 Input Data

In this section, the input data that the user needs to assign to execute the optimization problem for DAM, SRM, and IDMs is described. The input data sheets (highlighted in orange in the Excel file), and the overall description of each sheet are shown in Table 4-2. The input data includes the global parameters that should be assigned for each market optimization problem accordingly. The DVPP units data, the network data, and forecast data should be assigned separately in the corresponding Excel worksheet. In the following subsections, the input parameters in each Excel sheet are defined.

Table 4-2 Input data sheets to execute the optimization problem for DAM, SRM, and IDMs

Input data sheet	Description
Global_params	The global parameters that control the setting for different optimization models
Buses	The network buses data
TSO	The transmission system operator data request for reserve provision
DVPP_Units	The DVPP units type and location data
Line	The DVPP subnetwork lines data
NDRES	The ND-RESs data
STU	The STU data
DRES	The DRES data.
ESS	The ESS (TES and ES) data
Demand	The demand data
Energy_Forecast	The energy forecast data for ND-RES and STU in different electricity markets (DAM, SRM, and IDMs)
Price_Forecast	The electricity price forecast data in different electricity markets (DAM, SRM, and IDMs)

4.2.1 Global Parameters Data

The global parameters of the proposed tool, their value, their units, and the description of each one are presented in Table 4-3. This Excel sheet contains some of the key parameters that the user can modify to execute the optimization algorithm for each problem. The user needs to assign the market that the DVPP wants to participate, SRM data, the ESS (if any, including the inner storage of STUs), the network per unit data, and the uncertainty budgets for running the robust optimization problem for each market session.

Table 4-3 Global parameters sheet

Global parameters		Value	Unit	Description					
NDRES-STU ID		-	-	Identification of NDRES and STU for indexing (U)					
sMarket		0	[-]	Market to participate in. "-1" for DAM; "0" for SRM; "1-7" for IDMs					
sTime_SR		15	[min]	Required time for SR action					
sFraction_Time_SR		1	[-]	Max SR calls on duration time [hour] divided by 1 hour					
sEss_lower_bound		0.09	[pu]	Lower bound of ESS (TES and ES) energy at last period in schedule					
sEss_upper_bound		1	[pu]	Upper bound of ESS (TES and ES) energy at last period in schedule					
sIDM_start		0	[-]	Initial value for IDM1					
sK_theta		1	[pu]	STU output multiplier at startup					
sDelta		1	[hour]	Power-energy conversion factor					
sPower_base		100	[MVA]	Base apparent power					
sVoltage_base		10	[KV]	Base voltage					
sSRreserve_limit		0.15	[pu]	SR share that can be provided by VPP compared to its capacity					
pGamma_Price_DAM		0	[-]	Uncertainty budget of DAM price (continuous amount 0-24)					
pGamma_Price_SRM_up		0	[-]	Uncertainty budget of up SRM price (continuous amount 0-24)					
pGamma_Price_SRM_down		0	[-]	Uncertainty budget of down SRM price (continuous amount 0-24)					
pGamma_Price_IDM1		0	[-]	Uncertainty budget of IDM1 price (continuous amount 0-24)					
⋮		⋮	⋮	⋮					
pGamma_Price_IDM7		0	[-]	Uncertainty budget of IDM7 price (continuous amount 0-3)					
Gamma DAM			[-]	Uncertainty budget of NDRES and STU in DAM (continuous amount 0-24)					
Gamma SRM			[-]	Uncertainty budget of NDRES and STU in SRM (continuous amount 0-24)					
Gamma IDM1			[-]	Uncertainty budget of NDRES and STU in IDM1 (continuous amount 0-24)					
⋮		⋮	⋮	⋮					
Gamma IDM7			[-]	Uncertainty budget of NDRES and STU in IDM7 (continuous amount 0-3)					
NDRES-STU ID	Gamma DAM	Gamma SRM	Gamma IDM1	Gamma IDM2	Gamma IDM3	Gamma IDM4	Gamma IDM5	Gamma IDM6	Gamma IDM7
U3	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0

4.2.2 Buses Data

The buses data is presented in Table 4-4. The user needs to assign the name of the buses, their type (as reference bus (REF), common bus (C), or Point of Common Coupling (PCC)), their base voltage in kV, and PCC bus capacity.

Table 4-4 Buses data sheet

Bus parameters	Unit	Description		
Bus ID	-	Identification of bus for indexing (B)		
Bus Type	-	Specification for bus--reference bus (REF), common bus C, point of common coupling PCC--		
PCC ID	-	Identification of PCC bus (B)		
Base kV	[KV]	Base KV for computation in per unit		
PCC capacity	[MW]	Capacity of PCC bus		
Bus ID	Bus Type	Base kV	PCC ID	PCC capacity
B1	REF	66	B5	110
B2	C	66		
B3	C	66		
B4	C	66		
B5	PCC	132		
B6	C	66		
⋮	⋮	⋮		

4.2.3 TSO data

The Transmission System Operator (TSO) request for up and down reserve data is presented in Table 4-5. The user needs to set the proportion of up to down secondary reserve requested by the TSO.

Table 4-5 TSO data sheet

TSO parameters	Unit	Description	
Period	-	Identification of period (T)	
TSO up/down SR request	[-]	Relation between up and down SR requested by TSO (SR Bound for Spanish Market)	
Period	TSO up/down SR request		
T1	1.17		
T2	1.17		
T3	1.25		
⋮	⋮		
T24	1.33		

4.2.4 DVPP Units Type Data

In the DVPP_Units Excel sheet, the user can assign the DVPP units type (D-RES, ND-RES, STU, Demand (D), and ESS) and their location according to Table 4-6. Besides each storage system within an STU needs to be set. Note that the duplicated subtables with columns DVPP ID and Unit Type are needed for implementation purposes within GAMS.

Table 4-6 DVPP units data sheet

DVPP units parameters	Unit	Description					
VPP ID	-	Identification of DVPP unit for indexing (U)					
Bus ID	-	Identification of bus for indexing (B)					
Unit type	-	Identification of unit type for indexing (DRES, NDRES, STU, D, TES, ES)					
STU ID	-	Identification of STU unit (U)					
TES ID	-	Identification of TES unit connected to STU (U)					
DVPP ID	Bus ID	Unit type	DVPP ID	Unit type	STU ID	TES ID	
U1	B6	DRES	U1	DRES	U5	U9	
U2	B9	DRES	U2	DRES			
U3	B4	NDRES	U3	NDRES			
U4	B8	NDRES	U4	NDRES			
U5	B1	STU	U5	STU			
U6	B3	D	U6	D			
U7	B9	D	U7	D			
U8	B12	D	U8	D			
U9	B8	TES	U9	TES			

4.2.5 DVPP Subnetwork Lines Data

The DVPP subnetwork lines capacity, reactance, and sending and receiving ends are defined in the Excel sheet Lines, as shown in Table 4-7.

Table 4-7 DVPP subnetwork lines data sheet

Line parameters	Unit	Description
Line ID	-	Identification of line for indexing (L)
From Bus Number	-	Origin bus for line (B)
To Bus Number	-	Destination bus for line (B)
Capacity	[MW]	Power capacity of line
Reactance	[pu]	Line reactance

Line ID	Capacity	Reactance
L1	500	0.15
L2	500	0.15
L3	500	0.15
⋮	⋮	⋮

Line ID	From Bus Number
L1	B1
L2	B1
L3	B1
⋮	⋮

Line ID	To Bus Number
L1	B2
L2	B3
L3	B5
⋮	⋮

4.2.6 ND-RES Data

The data related to the ND-REsSs, except for their energy forecasts, is defined in the ND-RES Excel sheet (see Table 4-8). The user needs to assign minimum power production, operation cost, and SR ramp rate of each ND-RES unit.

4.2.7 STU Data

The parameters related to STU are depicted in Table 4-9. The user needs to assign, in the STU Excel sheet, the commitment parameters, operation cost, power block machine capacity, maximum electrical output, and the parameter related to linear form of piecewise function of power block. A separate Excel sheet (ESS - see Section 4.2.9), is used for the thermal storage of STU, given their similarities with other ESS technologies that can be defined.

Table 4-8 ND-RES data sheet

NDRES parameters	Unit	Description		
NDRES ID	-	Identification of NDRES (U)		
Min power	[MW]	Minimum power production of NDRES		
Operation Cost	[Euro/MWh]	Operation costs of NDRES		
SR Ramp Up	[MW/min]	SR ramp up rate of NDRES		
SR Ramp Down	[MW/min]	SR ramp down rate of NDRES		
NDRES ID	Min power	Operation Cost	SR Ramp Up	SR Ramp Down
U3	0	10	600	600

Table 4-9 STU data sheet

STU parameters		Unit	Description					
STU ID		-	Identification of STU units (U)					
Period		-	Identification of period (T)					
SOS set		-	Identification of SOS variable (I)					
Online periods prior IDMs		[hour]	Number of periods STU has been online prior to the first period of each IDM session. *Just set IDM1 value					
Offline periods prior IDMs		[hour]	Number of periods STU has been offline prior to the first period of each IDM session. *Just set IDM1 value					
Operation cost		[Euro]	Operation costs of STU units					
Machine capacity		[MW]	Machine Capacity of solar thermal power block					
Max electrical output		[MW]	Maximum electrical output power of STU unit					
Commit status t=0		[-]	Commitment status of STU at t=0					
Online periods prior t=1		[hour]	Number of periods STU has been online prior to the first period					
Offline periods prior t=1		[hour]	Number of periods STU has been offline prior to the first period					
Min up time		[hour]	Minimum up time of STU					
Min down time		[hour]	Minimum down time of STU					
Powerblock breakpoint		[MW]	Piecewise bounds on power block output					
Piecewise bounds		[pu]	Value of power block at breakpoint					
STU ID	Period	Online periods prior IDMs	Offline periods prior IDMs	STU ID	SOS set	Powerblock breakpoint	Piecewise bounds	
U5	T1	0	1	U5	I1	0	0	
U5	T2	0	1	U5	I2	18.99	0	
U5	T3	0	1	U5	I3	19	0.3	
U5	T4	0	1	U5	I4	40	0.35	
U5	T5	0	1	U5	I5	70	0.38	
U5	⋮	⋮	⋮	U5	I6	140	0.39	
U5	T24	0	1					
STU ID	Operation cost	Machine capacity	Max electrical output	Commit status t=0	Online periods prior t=1	Offline periods prior t=1	Min up time	Min down time
U5	15	128	55	0	0	1	6	6

4.2.8 D-RES Data

The D-RES parameters, which are defined in the Excel sheet DRES, are shown in Table 4-10. The user needs to determine the commitment parameters, production cost, maximum and minimum power production, and ramp rates of each D-RES.

Table 4-10 D-RES data sheet

DRES parameters		Unit	Description
DRES ID		-	Identification of DRES units (U)
Period		-	Identification of period (T)
SR status		-	SRM calls on condition (V)
Online periods prior IDMs		[hour]	Number of periods DRES has been online prior to the first period of each IDM session. *Just set IDM1 value
Offline periods prior IDMs		[hour]	Number of periods DRES has been offline prior to the first period of each IDM session. *Just set IDM1 value
Production cost		[Euro/MWH]	Production costs for DRES
Max power production		[MW]	DRES maximum power production
Min power production		[MW]	DRES minimum power production
Ramp up		[MW/h]	DRES ramping up limit
Ramp down		[MW/h]	DRES ramping down limit
Startup ramp up		[MW/h]	DRES startup ramping up limit
Shutdown ramp down		[MW/h]	DRES shutdown ramping down limit
Startup cost		[Euro]	Startup cost for dispatchable unit
Shutdown cost		[Euro]	Shutdown cost of DRES
Commit status t=0		-	Initial status of DRES
power production t=0		[MW]	Initial power production of DRES
SR ramp up		[MW/min]	Up SR ramp rate of DRES
SR ramp down		[MW/min]	Down SR ramp rate of DRES
Online periods prior t=1		[hour]	Number of periods DRES has been online prior to the first period
Offline periods prior t=1		[hour]	Number of periods DRES has been offline prior to the first period
Min up time		[hour]	Minimum up time of DRES
Min down time		[hour]	Minimum down time of DRES
Up SR t=0		[MW]	Up SR provided by DRES in time 0
Down SR t=0		[MW]	Down SR provided by DRES in time 0

DRES ID	Period	Online periods prior IDMs	Offline periods prior IDMs
U1	T1	0	1
U1	T2	0	1
U1	:	:	:
U1	T24	0	1
U2	T1	0	1
U2	T2	0	1
U2	:	:	:
U2	T24	0	1

SR status	DRES ID	Up SR t=0	Down SR t=0
V0	U1	0	0
V0	U2	0	0
V1	U1	0	0
V1	U2	0	0
V2	U1	0	0
V2	U2	0	0

DRES ID	Production cost	Max power production	Min power production	Ramp up	Ramp down	Startup ramp up	Shutdown ramp down	Startup cost	Shutdo wn cost
U1	7.5	0	0	1000	1000	1000	1000	200	200
U2	23	0	0	100	100	100	100	100	100

DRES ID	Commit status t=0	power production t=0	SR ramp up	SR ramp down	Online periods prior t=1	Offline periods prior t=1	Min up time	Min down time
U1	0	0	3.33	3.33	0	1	0	0
U2	0	0	0.15	0.15	0	1	3	3

4.2.9 ESS Data

The data of ESSs, including the STU thermal storage, is presented in Table 4-11. The ESS parameters include maximum/minimum and initial stored energy level, charging/discharging power capacity, charging/discharging efficiency, and ramp rates. Some parameters specific of BESs, such as self-degradation coefficient, BES installation costs, and the parameter that defines the operation cost related to expected life as a function of its cycles, are also found in this Excel sheet.

Table 4-11 ESS data sheet

ESS (ES & TES) parameters	Unit	Description				
ESS ID	-	Identification of ESS, including STU thermal storage (U)				
Self-degradation coefficient	[-]	Self-degradation coefficient of BES				
Max energy	[MWh]	Maximum energy capacity of ESS				
Min energy	[MWh]	Minimum energy capacity of ESS				
Discharging power	[MW]	Maximum discharging power of ESS				
Charging power	[MW]	Maximum charging power of ESS				
Initial energy	[MWh]	Initial energy stored in ESS				
Charging efficiency	[%]	Charging efficiency of ESS				
Discharging efficiency	[%]	Discharging efficiency of ESS				
ESS cost	[Euro]	Total BES unit cost including installation and operational costs				
Lifecycle slope	[-]	Slope of the linear approximation of the expected lifecycle of BES as function of cycles				
SR ramp up	[MW/min]	Up SR ramp rate of ESS				
SR ramp down	[MW/min]	Down SR ramp rate of ESS				
ESS ID	Self-degradation coefficient	Max energy	Min energy	Discharging power	Charging power	Initial energy
U9	0	1100	0	115	140	120
ESS ID	Charging efficiency	Discharging efficiency	ESS cost	lifecycle slope	SR ramp up	SR ramp down
U9	0.99	0.99	0	0	1000	1000

4.2.10 Flexible Demand Data

Demand data needs to be assigned according to Table 4-12 in the Demand Excel worksheet. The parameters to be defined comprise the different load profiles for DAM participation, the cost of each profile, the maximum deviation allowed for IDM participation, minimum daily energy consumption, ramp rates, and initial consumption of each demand.

Table 4-12 Flexible demand data sheet

Demand parameters	Unit	Description				
Demand ID	-	Identification of demand (U)				
Profile	-	Load profiles (LP)				
Period	-	Identification of period (T)				
SR status	-	SRM calls on condition (V)				
Demand	[MW]	Profiles of demands				
Cost	[Euro]	Load profile cost of each demand unit				
Negative fluctuation	[pu]	Maximum negative fluctuation of demand profile in IDM compared to DAM session				
Positive fluctuation	[pu]	Maximum positive fluctuation of demand profile in IDM compared to DAM session				
Min Energy	[MWh]	Minimum daily energy consumption requested by demand				
Ramp Up	[MW/h]	Demand pick up ramping limit				
Ramp Down	[MW/h]	Demand drop ramping limit				
SR Ramp Up	[MW/min]	Up SR ramp rate of demand				
SR Ramp Down	[MW/min]	Down SR ramp rate of demand				
Initial load level	[MW]	Initial load level for each demand				
Up SR t=0	[MW]	Up SR provided by demand at t=0				
Down SR t=0	[MW]	Down SR provided by demand at t=0				

Demand ID	Profile	Period	Demand
U8	lp1	T1	12.6
U8	lp1	T2	10.2
U8	lp1	T3	10.2
U8	:	:	:
U8	lp1	T24	15
U8	lp2	T1	9.6
U8	lp2	T2	9.6
U8	lp2	T3	5.4
U8	:	:	:
U8	lp2	T24	12
U8	lp3	T1	15.6
U8	lp3	T2	13.2
U8	lp3	T3	10.8
U8	:	:	:
U8	lp3	T24	15.6

Demand ID	Period	Negative fluctuation	Positive fluctuation
U8	T1	0.1	0.1
U8	T2	0.1	0.1
U8	T3	0.1	0.1
U8	:	:	:
U8	T24	0.1	0.1

SR status	Demand ID	Up SR t=0	Down SR t=0
V0	U8	0	0
V1	U8	0	0
V2	U8	0	0

Demand ID	Profile	Cost
U8	lp1	0
U8	lp2	0
U8	lp3	0

Demand ID	Min Energy	Ramp Up	Ramp Down	SR Ramp Up	SR Ramp Down	Initial load level
U8	360	1000	1000	166.66	166.66	15

4.2.11 Stochastic Energy Forecast Data

The energy forecast data of the stochastic sources of ND-RESs and STUs for the different markets are assigned in the *Energy_Forecast* Excel sheet, as shown in Table 4-13. Note that, for implementation efficiency purposes, only the median and downwards deviation of forecast data for each market session need to be defined, as the upwards deviation of stochastic energy forecast does not affect the result of the robust formulation proposed in this document (see Sections 3.3.3–3.3.8).

Table 4-13 Stochastic energy forecast data sheet

Energy forecast parameters		Unit	Description				
NDRES/STU ID		-	Identification of NDRES and STU (U)				
Period		-	Identification of period (T)				
Pavailable DAM		[MW]	Point forecasts of NDRES and STU production in time period t in DAM				
Dev Pavailable DAM		[MW]	Deviation of NDRES and STU production in time period t in DAM				
Pavailable SRM		[MW]	Point forecasts of NDRES and STU production in time period t in SRM				
Dev Pavailable SRM		[MW]	Deviation of NDRES and STU production in time period t in SRM				
Pavailable IDM1		[MW]	Point forecasts of NDRES and STU production in time period t in IDM1				
Dev Pavailable IDM1		[MW]	Deviation of NDRES and STU production in time period t in IDM1				
⋮		⋮	⋮				
Pavailable IDM7		[MW]	Point forecasts of NDRES production in time period t in IDM7				
Dev Pavailable IDM7		[MW]	Deviation of NDRES production in time period t in IDM7				
NDRES/ STU ID	Period	Pavailable DAM	Dev Pavailable DAM	Pavailable SRM	Dev Pavailable SRM	Pavailable IDM1	Dev Pavailable IDM1
U3	T1	0.78	0.28	0.78	0.14	2.48	0.86
U3	T2	1.2	0.31	1.79	0.19	2.55	0.6
U3	⋮	⋮	⋮	⋮	⋮	⋮	⋮
U3	T24	10.08	2.23	5.3	0.81	9.35	1.71
U5	T1	0	0	0	0	0	0
U5	T2	0	0	0	0	0	0
U5	⋮	⋮	⋮	⋮	⋮	⋮	⋮
U5	T24	0	0	0	0	0	0
NDRES/ STU ID	Period	Pavailable IDM2	Dev Pavailable IDM2	...		Pavailable IDM7	Dev Pavailable IDM7
U3	T1	3.13	0.39	...		2.96	0.68
U3	T2	0	0	...		0	0
U3	⋮	⋮	⋮	...		⋮	⋮
U3	T24	8.75	4.33	...		5.3	0.53
U5	T1	0	0	...		0	0
U5	T2	0	0	...		0	0
U5	⋮	⋮	⋮	...		⋮	⋮
U5	T24	0	0	...		0	0

4.2.12 Market Price Forecast Data

The mean and deviation values of price forecast for the markets to be considered in the optimization problem are defined in the Price_Forecas Excel sheet, and shown in Table 4-14. In the DAM optimization, the user needs to assign the price forecast for DAM and SRM. In the SRM optimization, the user needs to set the SRM and IDM#1 price forecast. Finally, for each IDM session, the corresponding price forecasts need to be updated.

Table 4-14 Market price forecast data sheet

Price forecast parameters		Unit	Description
Period		-	Identification of period (T)
DAM Price		[Euro/MWh]	Median DAM price forecast in the DAM
Pos dev DAM Price		[Euro/MWh]	Positive deviation of DAM price forecast in the DAM
Neg dev DAM Price		[Euro/MWh]	Negative deviation of DAM price forecast in the DAM
Up_SRM Price in DAM		[Euro/MWh]	Median up SRM price forecast in the DAM
Dev Up_SRM Price in DAM		[Euro/MWh]	Deviation of up SRM price forecast in the DAM
D_SRM Price in DAM		[Euro/MWh]	Median down SRM price forecast in the DAM
Dev D_SRM Price in DAM		[Euro/MWh]	Deviation of down SRM price forecast in the DAM
Up_SRM Price in SRM		[Euro/MWh]	Median up SRM price forecast in the SRM
Dev Up_SRM Price in SRM		[Euro/MWh]	Deviation of up SRM price forecast in the SRM
D_SRM Price in SRM		[Euro/MWh]	Median down SRM price forecast in the SRM
Dev D_SRM Price in SRM		[Euro/MWh]	Deviation of down SRM price forecast in the SRM
IDM1 Price in SRM		[Euro/MWh]	Median IDM1 price forecast in the SRM
Pos dev IDM1 Price in SRM		[Euro/MWh]	Deviation of IDM1 price forecast in the SRM
Neg dev IDM1 Price in SRM		[Euro/MWh]	Negative deviation of IDM1 prices forecasts in the SRM
IDM1		[Euro/MWh]	Median IDM1 price forecast
Pos dev IDM1		[Euro/MWh]	Positive deviation of IDM1 price forecast
Neg dev IDM1		[Euro/MWh]	Negative deviation of IDM1 price forecast
⋮		⋮	⋮
IDM7		[Euro/MWh]	Median IDM7 price forecast
Pos dev IDM7		[Euro/MWh]	Positive deviation of IDM7 price forecasts
Neg dev IDM7		[Euro/MWh]	Negative deviation of IDM7 price forecast

Period	DAM Price	Pos dev DAM Price	Neg dev DAM Price	Up_SRM Price in DAM	Dev Up_SRM Price in DAM	D_SRM Price in DAM	Dev D_SRM Price in DAM
T1	35.00	5.60	5.60	22.44	7.80	22.44	7.80
T2	27.35	4.30	4.30	25.99	4.50	25.99	4.50
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
T24	32.07	4.50	4.50	26.19	6.20	26.19	6.20

Period	Up_SRM Price in SRM	Dev Up_SRM Price in SRM	D_SRM Price in SRM	Dev D_SRM Price in SRM	IDM1 Price in SRM	Pos dev IDM1 Price in SRM	Neg dev IDM1 Price in SRM
T1	22.44	7.80	22.44	7.80	28.3	3.2	3.2
T2	25.99	4.50	25.99	4.50	19.95	2.2	2.2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
T24	26.19	6.20	26.19	6.20	34	4.1	4.1

Period	IDM1	Pos dev IDM1	Neg dev IDM1	...	IDM7	Pos dev IDM7	Neg dev IDM7
T1	28.3	3.2	3.2	...	29.72	3.8	3.8
T2	19.95	2.2	2.2	...	26.6	1.4	1.4
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
T24	34	4.1	4.1	...	29.72	0.8	0.8

4.3 Intermediate Data

For running SRM and IDMs optimization problems, certain output data of previous markets need to be considered as inputs. This *intermediate* data can automatically be obtained in the respective Excel sheets, highlighted in blue, by running the previous market sessions. Alternatively, the user can set/modify them manually if desired. The intermediate data sheets are listed in Table 4-15.

Table 4-15 Intermediate data sheets to execute the optimization problem for SRM and IDMs

Intermediate data sheet	Description
Trade_PCC	The energy and reserve traded in PCC in the previous markets
Trade_Units	The energy and reserve provided by units in the previous markets

4.3.1 Energy and Secondary Reserve Traded at the PCC

The intermediate data related to the energy and secondary reserve traded at the PCC is presented Table 4-16. For running the SRM, the user needs to have the energy traded in previous markets (i.e., the DAM). For running each IDM, the user needs to have the results of DAM, SRM and previous IDMs if the DVPP has previously participated in those markets.

Table 4-16 Energy and secondary reserve traded at PCC data sheet

Trade PCC parameters				Unit	Description			
SR status				-	SRM calls on condition (V)			
PCC ID				-	Identification of PCC bus (B)			
Period				-	Identification of period (T)			
PCC SR in SRM				[MW]	SR provided by DVPP at PCC buses in the SRM			
PCC up SR in SRM				[MW]	Up SR provided by DVPP at PCC buses in the SRM			
PCC down SR in SRM				[MW]	Down SR provided by DVPP at PCC buses in the SRM			
Traded energy DAM				[MW]	Traded energy by system operator in the DAM			
Traded energy previous markets				[MW]	The summation of traded energy by system operator in the previous markets			
UP SR in SRM				[MW]	UP SR provided by DVPP in the SRM			
Down SR in SRM				[MW]	Down SR provided by DVPP in the SRM			

SR status	PCC ID	Period	PCC SR in SRM	PCC ID	Period	PCC up SR in SRM	PCC down SR in SRM	Period	Traded energy DAM
V1	B5	T1	0.78	B5	T1	0.78	0.67	T1	-8.82
V1	B5	T2	1.48	B5	T2	1.48	1.27	T2	-8.4
V1	B5	:	:	B5	:	:	:	:	:
V1	B5	T24	8.23	B5	T24	8.23	6.19	T24	42.68
V2	B5	T1	-0.67						
V2	B5	T2	-1.27						
V2	B5	:	:						
V2	B5	T24	-6.19						

Period	Traded energy prev markets	Period	UP SR in SRM	Down SR in SRM
T1	-8.82	T1	0.78	0.67
T2	-8.4	T2	1.48	1.27
:	:	:	:	:
T24	42.68	T24	8.23	6.19

4.3.2 Energy and Secondary Reserve Provided by DVPP units

The intermediate data related to energy and secondary reserve provided by each DVPP unit is presented in Table 4-17. For running the SRM, the user needs the information about the scheduled energy of each DVPP unit in previous markets (i.e., the DAM). For running each IDM, the user needs, apart from the scheduled energy from previous markets, the commitment status of D-RESs and STUs, the energy stored in the ESSs (including the thermal storage of STUs), and the share of ESS energy capacity allocated to provide up/down secondary reserve.

Table 4-17 Energy and secondary reserve of DVPP units data sheet

Trade units parameters			Unit	Description		
VPP ID			-	Identification of VPP unit for indexing (U)		
DRES/STU ID			-	Identification of DRES/STU for indexing (U)		
ESS ID			-	Identification of ESS for indexing (U)		
Period			-	Identification of period (T)		
Units energy DAM			[MW]	Units fixed energy in the DAM		
Units energy previous market			[MW]	Units fixed energy in the previous session (DAM, SRM, or IDMs)		
DRES_STU Commit in previous market			[MW]	Commitment status of DRES and STU unit in the previous section of the market for the beginning period of ID2-ID7		
ESS Energy in previous market			[-]	Energy stored in the ESS (TES and ES) in the previous section of the market (SRM)		
ESS energy share for up SR in previous market			[MWh]	Share of ESS (TES and ES) energy capacity allocated to provide up SR in the previous section of the market (SRM)		
ESS energy share for down SR in previous market			[-]	Share of ESS (TES and ES) energy capacity allocated to provide down SR in the previous section of the market (SRM)		

VPP ID	Period	Units energy DAM	VPP ID	Period	Units energy previous market	DRES/STU ID	Period	DRES/STU Commit in previous market
U3	T1	0.78	U3	T1	0.78	U5	T1	0
U3	T2	1.2	U3	T2	1.2	U5	T2	0
U3	:	:	U3	:	:	U5	:	:
U3	T24	10.1	U3	T24	10.08	U5	T24	1
U5	T1	0	U5	T1	0			
U5	T2	0	U5	T2	0	ESS ID	Period	ESS Energy in previous market
U5	:	:	U5	:	:	U9	T1	120
U5	T24	44.6	U5	T24	44.6	U9	T2	120
U8	T1	9.6	U8	T1	9.6	U9	:	:
U8	T2	9.6	U8	T2	9.6	U9	T24	99
U8	:	:	U8	:	:			
U8	T24	12	U8	T24	12	ESS ID	ESSs energy share for up SR in previous market	ESSs energy share for down SR in previous market
						U9	0.11	0.062

4.4 Output Data

The final group of the Excel worksheets correspond to the output data that is obtained by solving the robust optimization algorithm. The worksheets, highlighted in red in the Excel-based user interface, are classified according to the market session that was solved, i.e., DAM, SRM and IDMs, as shown in Table 4-18. In the remainder of this Section, each worksheet is described in detail.

Table 4-18 Output data sheets with optimization results of DAM, SRM, and IDMs

Output data sheet	Description
DAM	Results of DAM
SRM	Results of SRM
IDM1-IDM7	Results of IDM1-IDM7

4.4.1 DAM Output Data

The output results of the DAM robust optimization problem are presented in Table 4-19. The information contained comprises the traded energy by DAM in the DAM, the first secondary reserve offer for SRM¹, the commitment status of the DVPP units, the expected economic results (incomes, costs and profits) from the market participation, and the convergence status of the robust optimization problem. With regard to the convergence status result, a value of State DAM = 1 reveals a successful completion of the optimization problem. Other values can be taken, for example, if the solver cannot find a solution or due to error in data that made the problem unbounded or infeasible. A full description of the status of the model status is available at the GAMS solver summary documentation².

4.4.2 SRM Output Data

The output data from SRM results are presented in Table 4-20. The outputs include the traded energy by DVPP in the IDM#1, the final secondary reserve offer for SRM, the commitment status of the DVPP units, the convergence status of optimization problem, and the expected economic results (incomes, costs and profits) from the market participation.

4.4.3 IDMs Output Data

The output data for IDM#1 results (the excel sheets for IDM2-IDM7 are similar) are presented in Table 4-21. Excel worksheets for IDM#2 through IDM#7 are similar. The data includes the adjustments of the DVPP traded energy in the IDM#1 with respect to the initial DAM offer, the commitment status of DVPP units, the convergence status of the optimization problem, and the expected economic changes compared to previous market results for participation in IDM#1.

¹ The user can decide whether to submit this offer to the secondary reserve market auction, or the final offer that results from solving the SRM problem if updated forecasts of uncertain profiles are available

² https://www.gams.com/latest/docs/UG_GAMSOutput.html#UG_GAMSOutput_ModelStatus

Table 4-19 DAM output data sheet

DAM results	Unit	Description
Period	-	Identification of period (T)
VPP ID	-	Identification of VPP unit for indexing (U)
SR status	-	SRM calls on condition (V)
Traded energy DAM	[MWh]	Traded energy by DVPP in the DAM
UP SR offer DAM	[MWh]	Up SR provided by DVPP in the DAM
Down SR offer DAM	[MWh]	Down SR provided by DVPP in the DAM
Commitment DAM	[-]	Commitment status of DRES and STU units
Generation DAM	[MWh]	Energy dispatch of unit u in time period t
Start Up DAM	[-]	DRES unit u started up condition
Shut Down DAM	[-]	DRES unit u shut down condition
UP SR DAM	[MW]	UP SR provided by units at time t for calls on condition v by DVPP operator
Down SR DAM	[MW]	Down SR provided by units at time t for calls on condition v by DVPP operator
State DAM	[-]	Convergence status of optimization problem (1 for optimal solution)
Revenue DAM	[Euro]	Revenue obtained in the DAM (DAM+SRM bids)
Cost DAM	[Euro]	Operation cost in the DAM (DAM energy)
Robust cost DAM	[Euro]	Electricity price robustness cost in the DAM (DAM + SRM price robustness)
Profit DAM	[Euro]	Profit obtained in the DAM (DAM+SRM profit)

State DAM	Revenue DAM	Cost DAM	Robust cost DAM	Profit DAM
1	19036.05	11799.7	0	7236.37

Period	Traded energy DAM	UP SR offer DAM	Down SR offer DAM
T1	-8.82	0	0
T2	-8.4	0	0
:	:	:	:
T24	42.68	0	0

VPP ID	Period	Commitment DAM	Generation DAM	Start Up DAM	Shut Down DAM
U3	T1		0.78		
U3	T2		1.2		
U3	:	:	:	:	:
U3	T24		10.08		
U5	T1	0	0	0	0
U5	T2	0	0	0	0
U5	:	:	:	:	:
U5	T24	1	44.6	0	0
U8	T1		9.6		
U8	T2		9.6		
U8	:	:	:	:	:
U8	T24		12		

SR status	VPP ID	Period	UP SR DAM	Down SR DAM
V1	U3	T1	0	0.78
V1	U3	T2	0	0
V1	U3	:	:	:
V1	U3	T24	0	0
V1	U5	T1	0	0
V1	U5	T2	0	0
V1	U5	:	:	:
V1	U5	T24	0	0
V1	U8	T1	0.78	0
V1	U8	T2	0	0
V1	U8	:	:	:
V1	U8	T24	0	0
V2	U3	T1	0	0.78
V2	U3	T2	0	0
V2	U3	:	:	:
V2	U3	T24	0	0
V2	U5	T1	0	0
V2	U5	T2	0	0
V2	U5	:	:	:
V2	U5	T24	0	0
V2	U8	T1	0.78	0
V2	U8	T2	0	0
V2	U8	:	:	:
V2	U8	T24	0	0

Table 4-20 SRM output data sheet

SRM results		Unit	Description	
Period		-	Identification of period (T)	
VPP ID		-	Identification of DVPP unit for indexing (U)	
SR status		-	SRM calls on condition (V)	
Traded Power SRM		[MW]	Traded power by DVPP in the SRM (IDM1 power)	
UP SR offer SRM		[MW]	Up SR provided by DVPP in the SRM	
Down SR offer SRM		[MW]	Down SR provided by DVPP in the SRM	
Commitment SRM		[-]	Commitment status of DRES and STU units in SRM	
Generation SRM		[MW]	Power dispatch of unit u in time period t in SRM	
Start Up SRM		[-]	DRES unit u started up condition in SRM	
Shut Down SRM		[-]	DRES unit u shut down condition in SRM	
UP SR SRM		[MW]	UP SR provided by units at time t for calls on condition v by DVPP operator in SRM	
Down SR SRM		[MW]	Down SR provided by units at time t for calls on condition v by DVPP operator in SRM	
State SRM		[-]	Convergence status of optimization problem (1 for optimal solution)	
Revenue SRM		[Euro]	Revenue obtained in the SRM (SRM+IDM1 bids)	
Cost SRM		[Euro]	Changes in operation cost compared to DAM	
Robust cost SRM		[Euro]	Electricity price robustness cost in the SRM (SRM + IDM1 price robustness)	
Profit SRM		[Euro]	Profit obtained in the SRM (SRM+IDM1 profit)	

State SRM	Revenue SRM	Cost SRM	Robust cost SRM	Profit SRM
1	1024.71	-1297.77	0	2322

Period	Traded Power SRM	UP SR offer SRM	Down SR offer SRM
T1	-1.07	0.78	0.67
T2	-0.89	1.48	1.27
⋮	⋮	⋮	⋮
T24	-12.58	8.23	6.19

VPP ID	Period	Commitment SRM	Generation SRM	Start Up SRM	Shut Down SRM
U3	T1		0		
U3	T2		0.31		
U3	⋮	⋮	⋮	⋮	⋮
U3	T24		5.3		
U5	T1	0	0	0	0
U5	T2	0	0	0	0
U5	⋮	⋮	⋮	⋮	⋮
U5	T24	1	36.14	0	0
U8	T1		9.89		
U8	T2		9.6		
U8	⋮	⋮	⋮	⋮	⋮
U8	T24		11.34		

SR status	VPP ID	Period	UP SR SRM	Down SR SRM
V1	U3	T1	0.78	0
V1	U3	T2	1.48	0
V1	U3	⋮	⋮	⋮
V1	U3	T24	0	0
V1	U5	T1	0	0
V1	U5	T2	0	0
V1	U5	⋮	⋮	⋮
V1	U5	T24	8.23	0
V1	U8	T1	0	0
V1	U8	T2	0	0
V1	U8	⋮	⋮	⋮
V1	U8	T24	0	0
V2	U3	T1	0	0
V2	U3	T2	0	0.31
V2	U3	⋮	⋮	⋮
V2	U3	T24	0	5.3
V2	U5	T1	0	0
V2	U5	T2	0	0
V2	U5	⋮	⋮	⋮
V2	U5	T24	0	0
V2	U8	T1	0	0.67
V2	U8	T2	0	0.96
V2	U8	⋮	⋮	⋮
V2	U8	T24	0	0.89

Table 4-21 IDM#1 output data sheet

SRM results	Unit	Description			
Period	-	Identification of period (T)			
VPP ID	-	Identification of VPP unit for indexing (U)			
Traded Energy IDM	[MWh]	Traded energy by DVPP in the IDM1			
Commitment IDM	[-]	Commitment status of DRES and STU units in IDM1			
Generation IDM	[MWh]	Energy dispatch of unit u in time period t in IDM1			
State IDM	[-]	Convergence status of optimization problem (1 for optimal solution)			
Revenue IDM	[Euro]	Revenue obtained in the IDM1			
Cost IDM	[Euro]	Changes in operation cost compared to SRM			
Robust cost IDM	[Euro]	Electricity price robustness cost in the IDM1			
Profit IDM	[Euro]	Profit obtained in the IDM1			
State IDM	Revenue IDM	Cost IDM	Robust cost IDM	Profit IDM	
1	4373.76	1339.56	0	3034.2	
Period	Traded Energy IDM	VPP ID	Period	Commitment IDM	Generation IDM
T1	1.36	U3	T1		2.48
T2	1.11	U3	T2		2.55
⋮	⋮	U3	⋮	⋮	⋮
T24	8.61	U3	T24		9.35
		U5	T1	0	0
		U5	T2	0	0
		U5	⋮	⋮	⋮
		U5	T24	1	44.6
		U8	T1		10.56
		U8	T2		10.56
		U8	⋮	⋮	⋮
		U8	T24		10.8

5 Illustrative Examples

The use and performance of the tool proposed to robustly optimize the participation of a DVPP in different electricity markets is illustrated in this Section. Three problems are solved, namely:

- Simultaneous DAM and SRM participation;
- Simultaneous SRM and IDM#1 participation; and
- IDM#4 participation.

The remainder of this section is organized as follows. Section 5.1 describes the test system considered for the examples discussed, and provides the input data used. The case studies that serve as illustrative examples are then presented in Section 5.2.

5.1 DVPP Description

The DVPP considered in this Section is distributed across a 12-node network connected to the main grid through a PCC as shown in Fig. 5-1. The network is a representation of a southern-Spanish region. The DVPP consists of an ND-RES (wind farm at bus 4), an STU (bus 1), and a residential load (bus 12). The STU power block and the wind farm both have rated capacities of 50 MW each. The thermal storage capacity of the STU is 1100 MWh. The operation costs of the wind farm and the STU are respectively 10 €/MWh and 15 €/MWh.

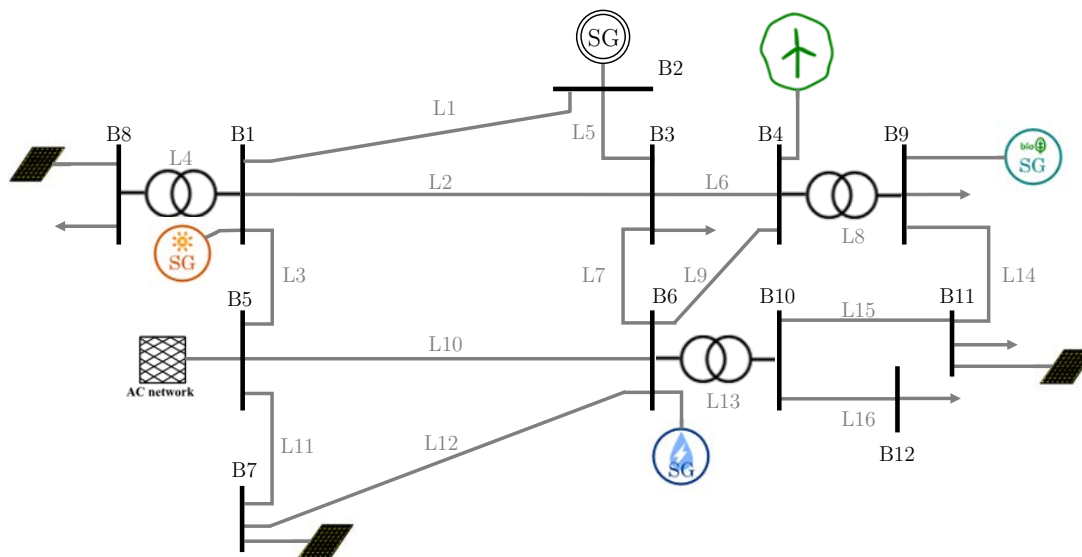


Figure 5-1 12-node network

For the residential demand, three different load profiles are available for choice at the DAM, as shown in Fig. 5-2. While fictitious, the base profile replicates the *default consumption activities* while other profiles are designed to perform peak shifting around it. The minimum daily consumption of each profile is 360 MWh. During IDM, the demand owner allows a 10% tolerance for demand movement over the selected profile at DAM.

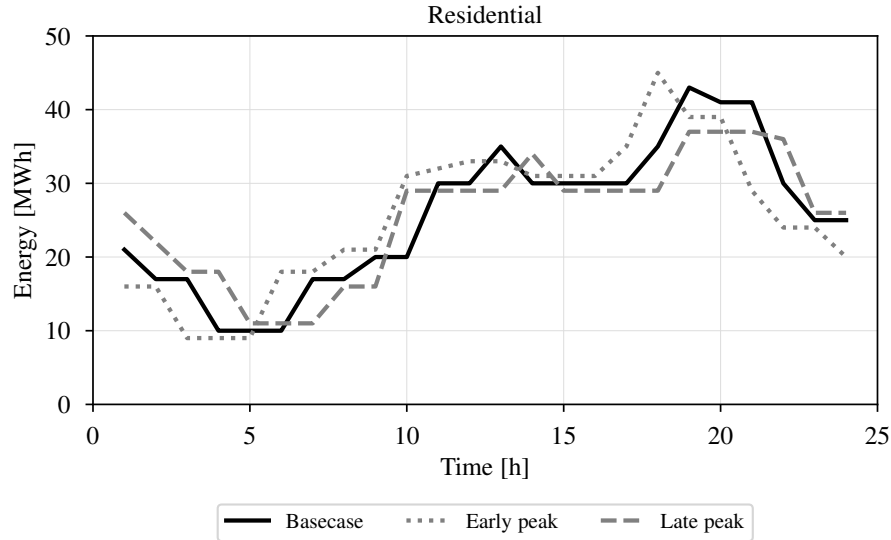


Figure 5-2 Residential demand profiles

The price forecast data for DAM, SRM, IDM#1, and IDM#4 used in the case studies of this Section are provided in Table 5-1. In the table, the price deviation values are considered symmetric. However, in the case studies of Section 5.2.2, different deviation values (as a percentage of deviation values in Table 5-1) are considered for asymmetric studies.

The energy forecast data of the wind farm for the aforementioned markets is included in Table 5-2. Finally, the thermal power production forecast of the STU solar field is provided in Table 5-3.

Table 5-1 Median and deviation values of DAM, SRM, IDM#1, and IDM#4 price forecasts

Period	$\tilde{\lambda}_t^{DA}$ [€/MWh]	$\tilde{\lambda}_t^{DA} / \tilde{\lambda}_t^{DA}$ [€/MWh]	$\tilde{\lambda}_t^{SR,\uparrow} / \tilde{\lambda}_t^{SR,\downarrow}$ [€/MW]	$\tilde{\lambda}_t^{SR,\uparrow} / \tilde{\lambda}_t^{SR,\downarrow}$ [€/MW]	$\tilde{\lambda}_{(k=1),t}^{ID}$ [€/MWh]	$\tilde{\lambda}_{(k=1),t}^{ID} / \tilde{\lambda}_{(k=1),t}^{ID}$ [€/MWh]	$\tilde{\lambda}_{(k=i),t}^{ID}$ [€/MWh]	$\tilde{\lambda}_{(k=i),t}^{ID} / \tilde{\lambda}_{(k=i),t}^{ID}$ [€/MWh]
T1	35.00	5.60	22.44	7.80	28.3	3.2	0	0
T2	27.35	4.30	25.99	4.50	19.95	2.2	0	0
T3	21.56	6.00	21.48	5.60	8.8	3.5	0	0
T4	20.43	5.00	22.51	4.30	8.8	2.4	0	0
T5	16.76	5.20	23.42	6.00	8.9	3.1	0	0
T6	17.37	4.80	23.21	4.80	10.7	1.8	0	0
T7	20.82	7.00	28.35	4.50	20	1.5	0	0
T8	35.71	3.20	22.66	5.60	39.19	4.6	34	1.5
T9	32.42	4.20	28.27	4.60	43.73	2.8	48.43	2.4
T10	36.79	6.70	28.06	7.40	44.1	3.4	45	1.9
T11	34.48	4.70	26.87	3.40	38	3.8	36	0.9
T12	33.36	5.00	22.28	3.80	36	4.8	39.3	2.2
T13	33.78	4.80	20.87	4.80	38.3	2.4	39.3	1.1
T14	32.74	6.70	20.57	5.00	37.85	4.1	38.78	3.5
T15	30.58	4.60	23.24	4.80	34.9	3.4	37	1.1
T16	24.88	7.40	27.14	4.50	31.69	2.8	32.2	2.8
T17	24.08	3.40	24.18	7.00	33.07	3.7	31.2	2.1
T18	29.63	3.80	22.9	3.20	34.36	1.8	29	1.5
T19	38.17	4.80	29.01	4.20	39.83	2.4	30	1.5
T20	52.91	5.00	21.74	6.70	44.04	3.7	47	3.5
T21	54.18	6.20	20.23	4.70	40.11	4.9	41.31	1.1
T22	49.89	5.70	18.68	4.80	35.1	3.5	35.1	2.8
T23	36.11	7.80	18.53	5.00	35	2.6	35	2.1
T24	32.07	4.50	26.19	6.20	34	4.1	26	1.5

Table 5-2 Median and deviation values of DAM, SRM, IDM#1, and IDM#4 wind farm production forecasts

Period	$\bar{P}_{r,t}^{DA}$ [MW]	$\bar{P}_{r,t}^{DA}$ [MW]	$\bar{P}_{r,t}^{SR}$ [MW]	$\bar{P}_{r,t}^{SR}$ [MW]	$\bar{P}_{r,t}^{ID}$ [MW]	$\bar{P}_{r,t}^{ID}$ [MW]	$\bar{P}_{r,t}^{ID}$ [MW]	$\bar{P}_{r,t}^{ID}$ [MW]
T1	0.78	0.28	0.78	0.14	2.48	0.86	1.92	0.49
T2	1.2	0.31	1.79	0.19	2.55	0.6	0	0
T3	0.15	0.04	1.29	0	1.07	0.48	0	0
T4	0.04	0	0.65	0.2	1.31	0.57	0	0
T5	0.04	0.02	0.41	0.15	0.88	0.43	0	0
T6	0.38	0.17	0.3	0.15	0.35	0.01	0	0
T7	1.72	0.62	1.72	0.51	0.32	0.13	0	0
T8	0.02	0	0.02	0	0.15	0.01	0	0
T9	0.24	0.04	0.24	0.06	0.13	0.03	0.13	0.03
T10	0.06	0	0.06	0.02	0.07	0.02	0.16	0.03
T11	1.26	0.36	1.26	0.26	0.02	0.01	0	0
T12	2.58	0.4	2.58	0.7	1.64	0.67	0.06	0
T13	5.45	1.86	3.87	1.37	2.63	0.83	2.38	0.84
T14	8.45	1.98	8.4	4.07	9.18	3.55	7.69	3.11
T15	15.96	7.17	14.04	6.54	16.33	2.04	16.97	4.62
T16	22.69	8.1	18.7	4.44	22.35	1.56	25.64	10.97
T17	24.92	11.44	24.71	5.09	29.64	7.28	28.58	5.5
T18	21.22	10.28	26.6	9.09	30.36	1.37	29.63	1.53
T19	21.14	1.79	20.88	6.05	26.98	2.78	26.76	8.75
T20	20	1.54	19.69	4.3	21.26	9.89	22.24	2.47
T21	16.31	4.84	17.03	8.33	18.2	7.14	15.68	6.99
T22	15.51	6.18	14.49	3.03	14.56	4.32	13.23	2.22
T23	11.92	2.81	11.75	0.92	11.75	5.64	11.69	4.51
T24	10.08	2.23	5.3	0.81	9.35	1.71	10.53	1.81

Table 5-3 Median and deviation values of DAM, SRM, IDM#1, and IDM#4 STU solar field production forecasts

Period	$\bar{P}_{\theta,t}^{DA}$ [MW]	$\bar{P}_{\theta,t}^{DA}$ [MW]	$\bar{P}_{\theta,t}^{SR}$ [MW]	$\bar{P}_{\theta,t}^{SR}$ [MW]	$\bar{P}_{\theta,t}^{ID}$ [MW]	$\bar{P}_{\theta,t}^{ID}$ [MW]	$\bar{P}_{\theta,t}^{ID}$ [MW]	$\bar{P}_{\theta,t}^{ID}$ [MW]
T1	0	0	0	0	0	0	0	0
T2	0	0	0	0	0	0	0	0
T3	0	0	0	0	0	0	0	0
T4	0	0	0	0	0	0	0	0
T5	0	0	0	0	0	0	0	0
T6	0	0	0	0	0	0	0	0
T7	0	0	0	0	0	0	0	0
T8	0	0	0	0	0	0	0.01	0.01
T9	80.59	61.67	88.76	64.34	88.76	64.34	116.85	57.07
T10	197.31	110.04	211.31	139.4	211.31	139.4	248.61	122.27
T11	207.47	110.3	219.38	144.18	219.38	144.18	222.09	118.42
T12	198.71	111.08	205.5	131.56	205.5	131.56	188.37	115.32
T13	184.67	122.81	185.63	111.49	185.63	111.49	169	96.81
T14	176.42	111.93	173.65	98.12	173.65	98.12	154.88	88.42
T15	177.91	99.23	172.16	94.65	172.16	94.65	153.99	84.83
T16	184.15	109.07	176.63	114.29	176.63	114.29	162.3	78.46
T17	184.86	102.83	177.04	99.78	177.04	99.78	168	96.12
T18	164.88	88.76	155.47	89.24	155.47	89.24	150.74	89.39
T19	54.18	39.4	50.13	37.93	50.13	37.93	48.68	37.16
T20	0	0	0	0	0	0	0	0
T21	0	0	0	0	0	0	0	0
T22	0	0	0	0	0	0	0	0
T23	0	0	0	0	0	0	0	0
T24	0	0	0	0	0	0	0	0

5.2 Case Studies

5.2.1 Sensitivity Analysis of Uncertainty Budget

The sensitivity analysis is performed for different value of price and energy uncertainty budgets of the robust formulation for different electricity markets, namely DAM, SRM, IDM#1 IDM#4. The impact of asymmetric deviation of DAM price on DVPP decisions for participation in the electricity market is also analyzed and discussed.

In Section 5.2.1.1, the DAM robust formulation results are provided (see Table 3-5). In the DAM, the DVPP optimizes the energy of its units for DAM bidding as well as the participation in the secondary reserve. In Section 5.2.1.2, the SRM robust formulation results are analyzed. The DVPP optimizes the reserve as well as the power adjustments in the first IDM. Finally, in Section 5.2.1.3, the sensitivity analysis for IDM#4 is presented. Note that other IDMs are omitted in these illustrative examples as their robust behavior are similar.

5.2.1.1 DAM and SRM

Figure 5-3 compares the traded power in the DAM in the deterministic case (i.e., when there is not uncertainty in price or energy) with a case where uncertainty in DAM price is considered by assuming a DAM uncertainty budget $\Gamma^{\text{DA}} = 5$. The DAM price forecast range is also depicted in Fig. 5-3. The DVPP is a net energy buyer in the electricity market in the first hours of the day for both cases due to low power production from the RESs in the DVPP, which does not suffice to supply its internal demand. After hour 9, the DVPP production increases mainly due to the STU, and it sells electricity to the market.

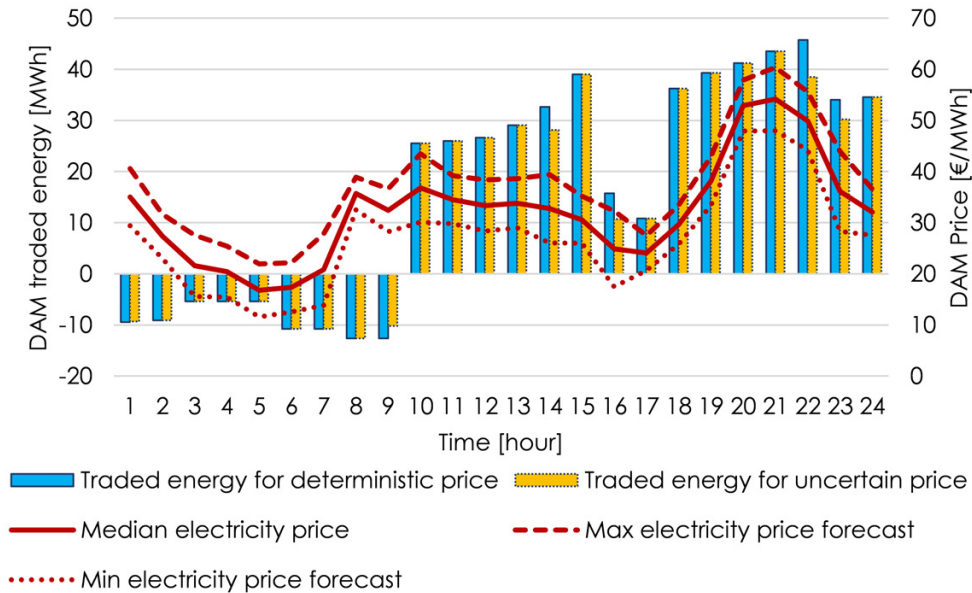


Figure 5-3 DAM electricity price forecast range and DAM traded power for deterministic case ($\Gamma^{\text{DA}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = 0$), and uncertain case ($\Gamma^{\text{DA}} = 5$; $\Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = 0$)

In the uncertain case, the electricity prices in 5 hours change in a way to apply the worst income reduction for the DVPP. The worst price scenario when the DVPP is a net seller/buyer of electricity corresponds to the minimum/maximum value in its forecast range. This is observed by comparing the solid and dashed red lines in Fig. 5-3. Overall, robustness against uncertainties generally implies lower amounts of energy bought (see hour 9) and sold (see hours 13, 16, and 21-23). Note that differences in the traded power between deterministic and uncertain cases might not be observed only in a number of hours equal to the value of the uncertainty budget. Indeed, only Γ^{DA} periods would see their price affected, but this might not be reflected in the power traded in those hours only, as the optimization algorithm could decide to move the energy traded more (or even less) hours.

The DVPP will to sell/buy electricity is decreased in uncertain case. However, the changes in traded power can be for more or less hours and also for different hours as those 5 worst hours. This is due to the fact that due to interconnecting constraints in the optimization problem, such as energy constraints of ESS and minimum demand energy constraint, other periods can be used for energy arbitrage.

Figure 5-4 shows DAM traded energy, the available wind farm energy, and the STU available thermal energy for different uncertainty budget conditions: optimistic (deterministic) case ($\Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} = 0$), pessimistic case ($\Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} = 24$), and two intermediate cases ($\Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} = 2$ and $\Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} = 5$). By increasing the uncertainty budget, the hours that impose the highest deviations in energy according to energy forecast are selected as the worst cases. For instance, hours 17 and 18 for wind production and hours 13 and 14 for available solar energy are the worst hours from deviation perspective for each technology. For low values of uncertainty budget, the DVPP is mostly a seller in the electricity market. However, for higher values of uncertainty budget, the DVPP needs to buy energy in the electricity market to cover for the forecast fluctuation of its ND-RES and STU energy and also to supply its demand.

Figure 5-5a) displays the DAM profit of DVPP for different DAM and SRM price uncertainty budgets. In Case 1, the DAM price uncertainty budget Γ^{DA} is increased from 0 to 24 in unity steps, whereas SRM price uncertainty is omitted ($\Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = 0$). By increasing DAM uncertainty budget, the DVPP income decreases with a higher slope for lower values of uncertainty budget compared to greater uncertainty budgets. This trend is expected as the worst cases of price deviations are selected first in the robust formulation.

In Case 2, the DAM price uncertainty budget is neglected ($\Gamma^{\text{DA}} = 0$) and SRM price uncertainty is increased from 0 to 24. The share of income reduction by increasing the uncertainty budget compared to Case 1 is smaller as most part of income comes from the DAM. The results for Case 3 show that by considering both DAM and SRM price uncertainty the income reduction is more than two previous cases.

Figure 5-5b) shows the DAM robustness cost for the above cases (see last line of Eq. 3.2). By increasing the uncertainty budget, a similar trend for robustness cost is observed for Case 1 through Case 3. High values of uncertainty budget imply lower increases in the robustness cost compared to lower values of uncertainty budget.

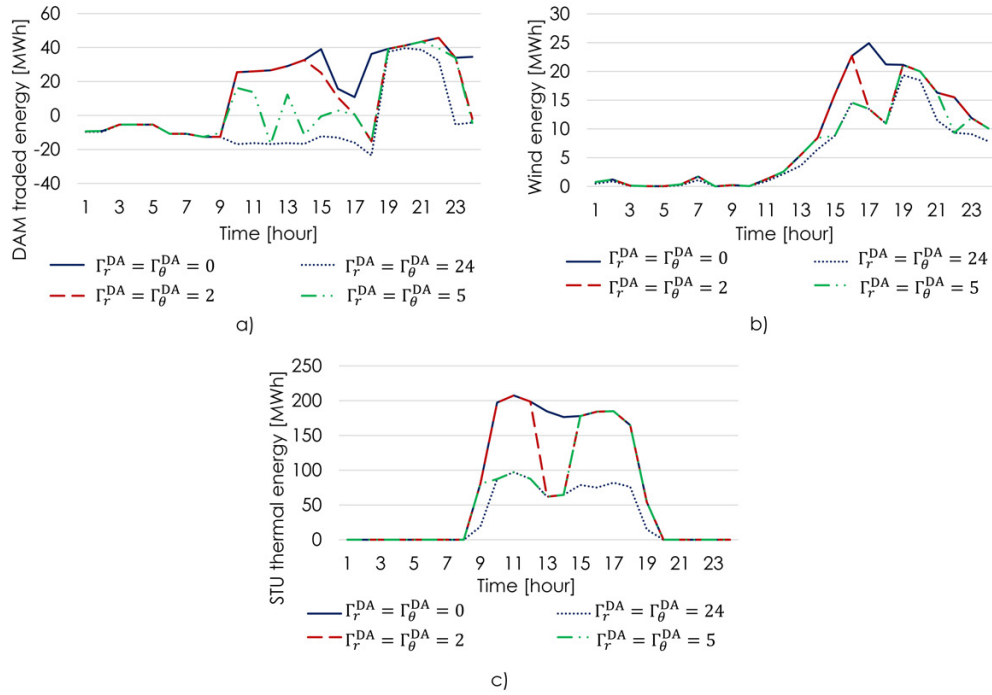


Figure 5-4 Impact of different uncertainty budgets on a) DVPP traded energy; b) wind farm available energy; and c) STU available energy

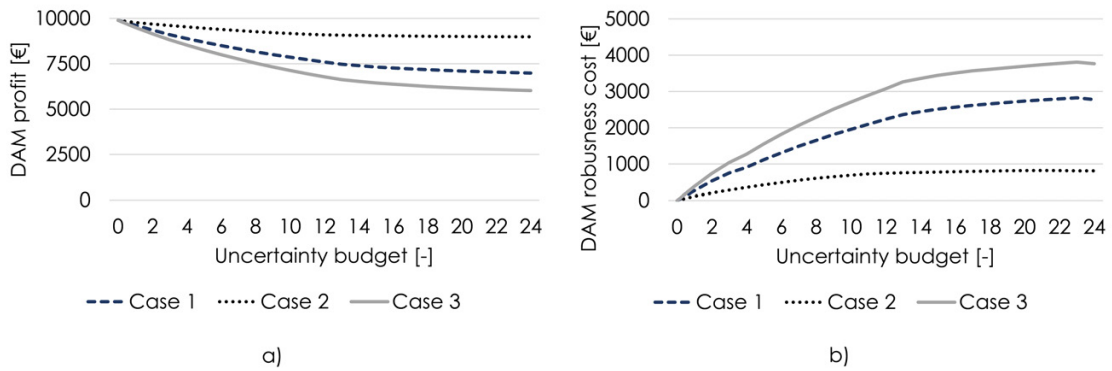


Figure 5-5 DAM profit and robustness cost for different DAM and SRM uncertainty budgets - **Case 1:** $\Gamma^{\text{DA}} \in [0, 24]$, $\Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = 0$; **Case 2:** $\Gamma^{\text{DA}} = 0$, $\Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} \in [0, 24]$; **Case 3:** $\Gamma^{\text{DA}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} \in [0, 24]$

Figure 5-6 shows the sensitivity of the DAM objective function for different values of wind farm production and STU thermal production uncertainty budgets. Three cases are compared, similar to the cases discussed in Fig. 5-5. Case 4 shows the DAM profit when only wind farm uncertainty is considered, while Case 5 depicts the result when the uncertainty of STU solar field thermal production is considered alone. Case 6 represents the DAM profit by considering both uncertainties simultaneously. The DAM profit decreases by increasing the uncertainty budget of wind farm and STU production. The impact of STU production is higher than wind farm for the considered sample day. Moreover, increasing the uncertainty budget $\Gamma_{\theta}^{\text{DA}}$ beyond a value of 11 does not affect the DAM profit reduction, since the productions of the STU solar field is zero for several hours (in the evening). The uncertainty in price is neglected for all above cases so the robustness cost due to uncertainty in price is zero.

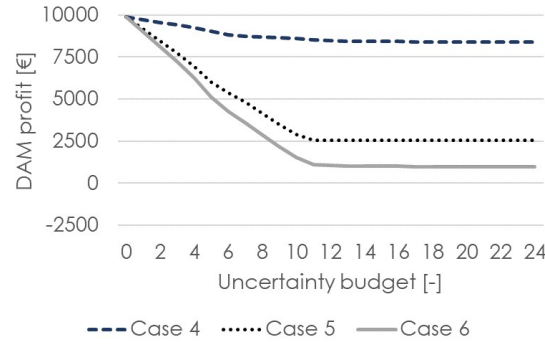


Figure 5-6 DAM profit for different wind farm and STU production uncertainty budgets - **Case 4:** $\Gamma_r^{\text{DA}} \in [0, 24]$, $\Gamma_\theta^{\text{DA}} = 0$; **Case 5:** $\Gamma_r^{\text{DA}} = 0$, $\Gamma_\theta^{\text{DA}} \in [0, 24]$; **Case 6:** $\Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} \in [0, 24]$

Figure 5-7 shows the DAM profit and robustness cost when all price uncertainties are considered (Case 7), when all energy energy uncertainties are considered in (Case 8), and when all uncertainties, both in price and energy, are included (Case 9).

Comparing all cases, it can be observed that, in the scenario considered, the majority of the DVPP profit reduction comes from the energy uncertainty. The negative profit for high values of uncertainty budgets in Case 9 is due to the fact the DVPP does not have enough energy from its RESs to internally supply its demand, and thus needs to buy electricity from the market. From Fig. 5-7b), it can be seen that the robustness cost for Case 9 is smaller than Case 7 since by reducing the wind farm and solar field production due to energy uncertainty, the total profit decreases and as a result the share of income reduction is lower compared to the case that energy uncertainty is not considered.

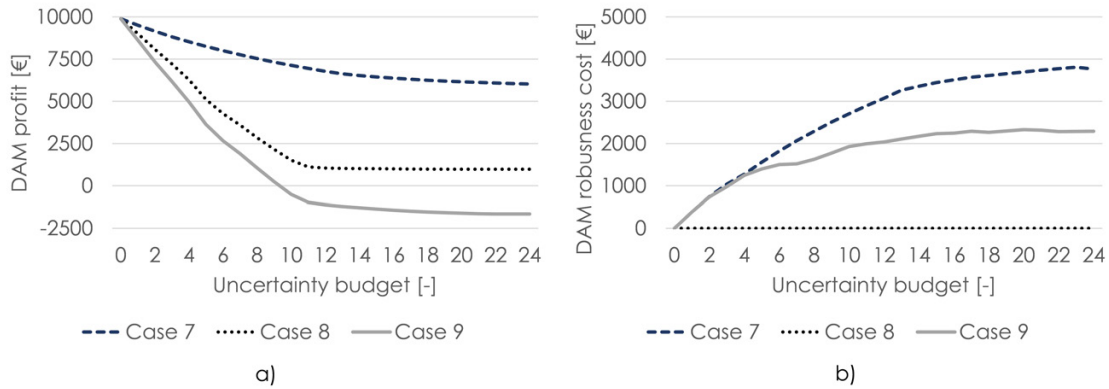


Figure 5-7 DAM profit and robustness cost for different price and energy uncertainty budgets - **Case 7:** $\Gamma^{\text{DA}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} \in [0, 24]$, $\Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} = 0$; **Case 8:** $\Gamma^{\text{DA}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = 0$, $\Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} \in [0, 24]$; **Case 9:** $\Gamma^{\text{DA}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = \Gamma_r^{\text{DA}} = \Gamma_\theta^{\text{DA}} \in [0, 24]$

5.2.1.2 SRM and IDM#1

Figure 5-8a) depicts the SRM profit of the DVPP for different SRM and IDM#1 price uncertainty budgets. In Case 1, the IDM#1 price uncertainty budget is increased from 0 to 24 in unity steps, and SRM price uncertainty is neglected. As the volume of traded energy in IDM#1 is small compared to the reserve provided in the market in the scenario considered, by increasing the IDM#1 price uncertainty budget, minor variations are observed in the overall profit.

In Case 2, the IDM#1 price uncertainty budget is neglected and SRM price uncertainty is increased from 0 to 24. The share of income reduction by increasing the uncertainty budget compared to Case 1 is higher as most part of the income comes from providing reserve. Results for Case 3 show that by considering both IDM#1 and SRM price uncertainty, the income reduction is the highest of the three cases, as expected.

From Fig. 5-8a) it can be observed that, by increasing the uncertainty budget, the robustness cost for all above cases increases. However, for high values of the uncertainty budget, increasing its value has substantially less impact than for lower values. This again demonstrates that the worst periods from the point of view of the objective function are first selected as the budget increases.

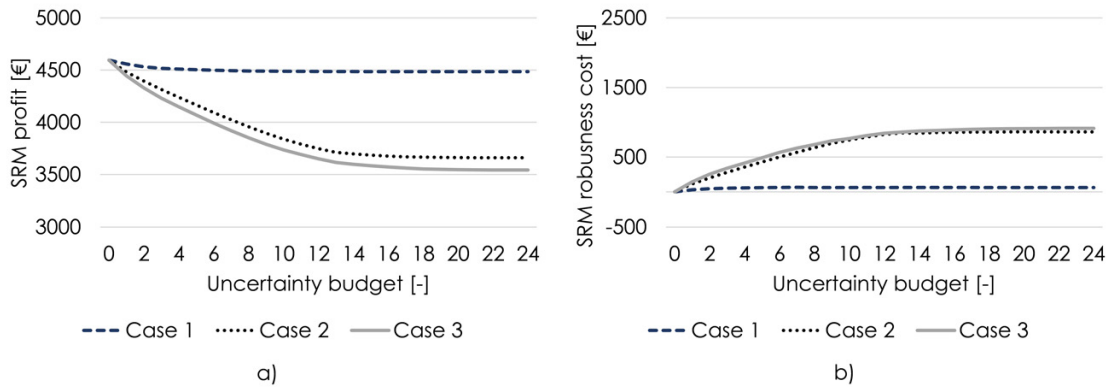


Figure 5-8 SRM profit and robustness cost for different SRM and IDM#1 price uncertainty budgets - **Case 1:** $\Gamma_{(k=1)}^{\text{ID}} \in [0, 24]$; $\Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = 0$;

Case 2: $\Gamma_{(k=1)}^{\text{ID}} = 0$; $\Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} \in [0, 24]$;

Case 3: $\Gamma_{(k=1)}^{\text{ID}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} \in [0, 24]$

Figure 5-9 depicts the SRM profit and robustness cost for different price and energy uncertainties. Case 4 considers only the uncertainty in IDM#1 and SRM prices. Case 5 provides the results assuming the uncertainty in the wind farm and solar field available energy. In Case 6, both price and energy uncertainties are considered. The share of profit reduction is much higher when only uncertainty in energy is considered (Case 5) compared to Case 4. Case 6 provides deep insight about an appropriate bidding strategy of the DVPP in the SRM considering all uncertainties in price and energy.

From Fig. 5-9b), it can be seen that the robustness cost for Case 4 is substantially smaller than Case 6. As the price uncertainty is neglected in Case 5, the robustness cost in this case is zero.

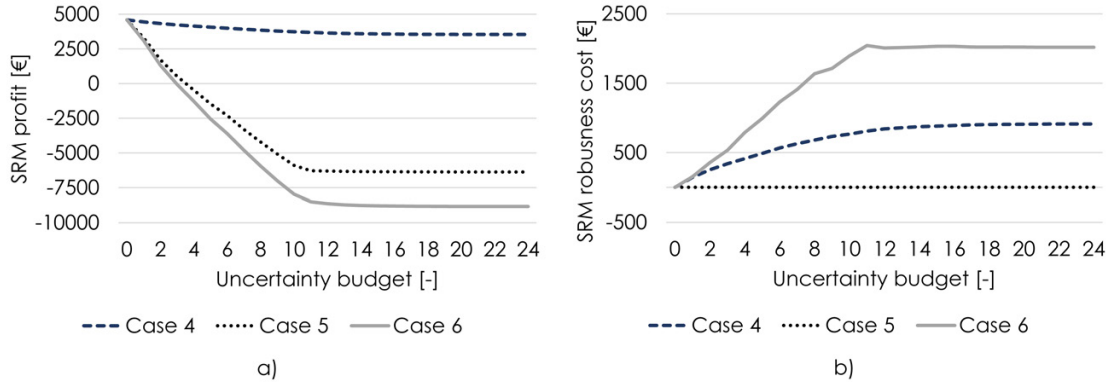


Figure 5-9 SRM profit and robustness cost for different SRM and IDM#1 price and energy uncertainty budgets - **Case 4:** $\Gamma_{(k=1)}^{\text{ID}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} \in [0, 24]$; $\Gamma_r^{\text{SR}} = \Gamma_\theta^{\text{SR}} = 0$;
Case 5: $\Gamma_{(k=1)}^{\text{ID}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} = 0$; $\Gamma_r^{\text{SR}} = \Gamma_\theta^{\text{SR}} \in [0, 24]$;
Case 6: $\Gamma_{(k=1)}^{\text{ID}} = \Gamma^{\text{SR},\uparrow} = \Gamma^{\text{SR},\downarrow} \in [0, 24]$; $\Gamma_r^{\text{SR}} = \Gamma_\theta^{\text{SR}} \in [0, 24]$

5.2.1.3 IDM#4

In this section, IDM#4 as an example of IDMs is considered for robustness sensitivity analysis. The analysis for other IDMs is similar and thus is omitted here.

In the IDM#4, the DVPP can adjust its DAM schedule for periods 8 through 24. Therefore, the uncertainty budgets can take values in the interval $[0, 17]$, and not $[0, 24]$.

The results for IDM#4 profit and robustness costs for different uncertainty budget values in price and energy are depicted in Fig. 5-10. Case 1 considers price uncertainty only. Case 2 depicts the results when only the energy uncertainty is presented. In Case 3, all uncertainties in price and energy are considered. The IDM#4 profit reduction in Case 1 is small compared to other cases. The majority of the profit reduction comes from uncertainty in energy.

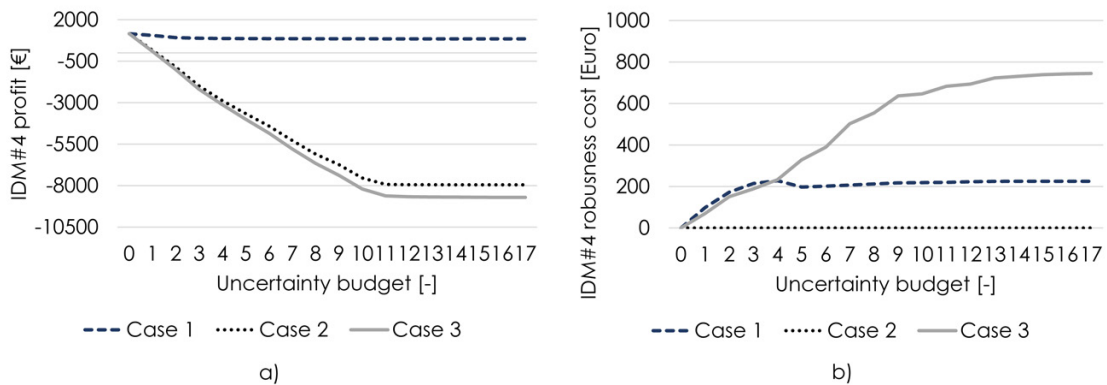


Figure 5-10 IDM#4 profit and robustness cost for different price, ND-RES and STU uncertainty budgets - **Case 1:** $\Gamma_{(k=4)}^{\text{ID}} \in [0, 17]$; $\Gamma_{(k=4),r}^{\text{ID}} = \Gamma_{(k=4),\theta}^{\text{ID}} = 0$;
Case 2: $\Gamma_{(k=4)}^{\text{ID}} = 0$; $\Gamma_{(k=4),r}^{\text{ID}} = \Gamma_{(k=4),\theta}^{\text{ID}} \in [0, 17]$;
Case 3: $\Gamma_{(k=4)}^{\text{ID}} = \Gamma_{(k=4),r}^{\text{ID}} = \Gamma_{(k=4),\theta}^{\text{ID}} \in [0, 17]$;

As observed from Fig. 5-10b), for uncertainty budget values lower than 4, the robustness cost for Case 1 is higher than Case 3, with the trend reversed for values higher than 4. This is due to the fact that, for high value of energy uncertainty budgets, $\Gamma_{(k=4),r}^{ID}$ and $\Gamma_{(k=4),\theta}^{ID}$, the DVPP needs to buy a significant share of energy from the market at a price that is much higher than average forecast price, which in turn leads to higher robustness costs. For values lower than 4, the most part of profit reduction in Case 3 comes from reduction in revenue not robustness cost which explains the logic behind the robustness cost trend in Cases 1 and 3.

5.2.2 Asymmetry in Uncertainties

This section illustrates the behavior of the proposed robust optimization model for DVPPs. To this aim, the result of DAM profit and robustness cost for different deviation patterns (both symmetric and asymmetric) of DAM price forecast is shown in Fig. 5-11. For the sake of clarity, and Without loss of generality, the uncertainty in the SRM price is neglected in this study.

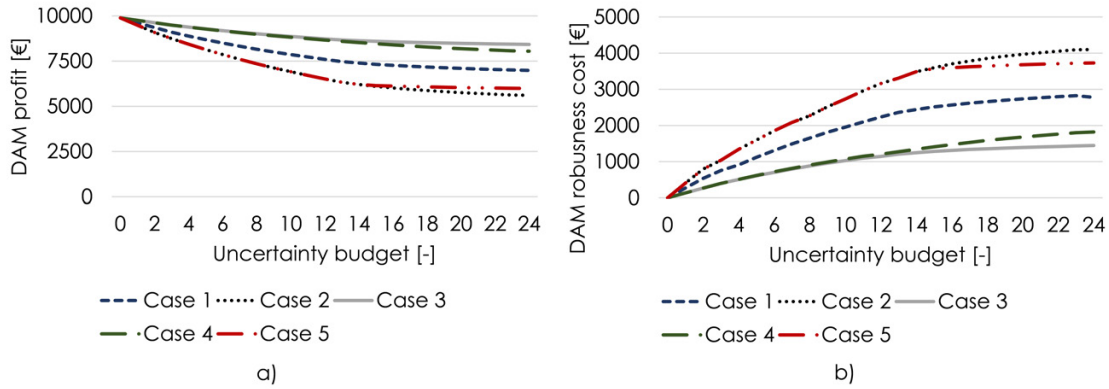


Figure 5-11 DAM profit and robustness cost for symmetric and asymmetric DAM price uncertainty budgets - **Case 1:** $\check{\lambda}_t^{DA} = \hat{\lambda}_t^{DA} = \hat{\lambda}_{t,base}^{DA}$; **Case 2:** $\check{\lambda}_t^{DA} = \hat{\lambda}_t^{DA} = 1.5\hat{\lambda}_{t,base}^{DA}$; **Case 3:** $\check{\lambda}_t^{DA} = \hat{\lambda}_t^{DA} = 0.5\hat{\lambda}_{t,base}^{DA}$; **Case 4:** $\check{\lambda}_t^{DA} = 1.5\hat{\lambda}_{t,base}^{DA}$, $\hat{\lambda}_t^{DA} = 0.5\hat{\lambda}_{t,base}^{DA}$; **Case 5:** $\check{\lambda}_t^{DA} = 0.5\hat{\lambda}_{t,base}^{DA}$, $\hat{\lambda}_t^{DA} = 1.5\hat{\lambda}_{t,base}^{DA}$

Case 1 considers the same deviation upwards and downwards deviation in DAM price forecast (i.e., it is symmetric), and equal to the values provided in Table 5-1, hereinafter referred to as $\hat{\lambda}_{t,base}^{DA}$. Case 2 considers a scenario where a symmetric deviation which is 50% higher than in Case 1, whereas a 50% decrease in DAM price deviation (symmetric) is presented in Case 3. Case 4 considers an asymmetric scenario in which the upwards DAM price deviation is 50% lower than $\hat{\lambda}_{t,base}^{DA}$, and the downwards price deviation is increased by 50%. Finally, in Case 5, the upwards and downwards DAM price deviations are increased and decreased by 50%, respectively, with respect to $\hat{\lambda}_{t,base}^{DA}$.

From Fig 5-11a), it can be observed that for the symmetric cases (Cases 1-3), the DAM profit is increased by reducing the price volatility and vice versa. The DAM profit for asymmetric Case 4 is slightly reduced compared to Case 3, since the DVPP is a seller in the energy market so increasing the downwards deviation of price does not have a significant impact. However, by considering a higher upwards deviation of price in Case 5 compared to Case 3, the DAM profit of DVPP is significantly decreased.

Figure 5-11b) shows the DAM robustness cost for the above cases. The robustness cost has higher values when assuming higher uncertainties in prices in Case 2. In Case 3, by considering a smaller value for price deviation compared to other cases, the robustness cost also has lower value. Note that, for Cases 4 and 5, differences with respect to Cases 3 and 2 are seen only for high values of the robustness budget. This is due to the main role of the DVPP as a net energy seller to the market in the scenario considered.

6 Conclusions and Future Work

This deliverable concludes Task 5.2, and proposes an upgrade of the DVPP model core that optimizes its operation and configuration when participating in European energy and ancillary service markets, and that was developed in Task 5.1.

In the model core from Task 5.1, a priori uncertain input data were considered as exact realizations of their forecast values. This assumption, while useful to test and validate the functionalities of the overall optimization model, it greatly limits its real-world application as the actual value of the objective function might substantially differ from the simulation results. Moreover, schedules resulting from the optimization algorithm might not be feasible in reality due to, e.g., lack of available energy resources.

This document proposes an approach to duly account for the different uncertainties that characterize the RES-based DVPPs studied in the POSYTYF project. Such an approach is based on the so-called Robust Optimization, which accurately models the DVPP uncertainties when determining the optimal participation of the DVPP in the different markets considered. The Robust Optimization solves the optimization problem for the *worst-case realization* of the uncertain range, which is defined by the median and upwards/downwards deviations of the uncertain distributions.

This model has been implemented in the widely-used commercial software GAMS. The tool for the optimal operation of DVPPs under uncertainty is completed with a user-friendly interface developed in MS Excel where the user can define, in a simple and organized way, all the input data required by the model. Results of significance from the optimization algorithm are also conveniently organized in the user interface for at-a-glance visualization and interpretation.

The operation and performance of the proposed tool is discussed by means of a comprehensive set of illustrative examples that serve to validate the model. Simulation results show that the Robust Optimization offers the possibility to define, from the user's side, the boundaries of the uncertain range based on the strategy to follow, whether optimistic, neutral, or conservationist.

Future work directions include considering the uncertainty of demand consumption in the proposed model. Such uncertainties will be modeled similarly to those of ND-RES and STU available energy. Uncertainty in prices of ancillary services other than the secondary reserve provision (such as inertia/primary frequency reserve provision, congestion management service, etc.) could also be readily included in the proposed model.

How correlations of the different uncertainties in the problem affect the results will also be duly analyzed. So far, it has been considered that the uncertainties are not correlated, i.e., the behaviour of given uncertain parameter does not affect others. However, some parameters might show considerable correlations (e.g., DAM and IDM prices, solar irradiation or wind speeds at plants geographically close, etc), which can distort the optimization results.

The proposed model allows the user to define the desired level of robustness for the optimization tool. However, how to decide, for each given scenario, the required uncertainty budget to play an optimist, neutral or conservationist role in the market is not an straightforward decision for the user. With this aim, a probabilistic assessment to define the uncertainty budget associated with the role pursued by the DVPP operator will be carried out.

The fully-fledged optimization model will be used to thoroughly analyze different DVPP configurations in a variety of market structures and scenarios. This will include the possibility of large DVPPs that might show an impact on the cleared market prices, thus becoming price makers. Task 5.4 will focus on the definition of the scenarios and case studies that will be considered for simulations. All analyses will be then carried out in Tasks 5.5 and 5.6, and results will be presented and compared with solutions based on electrochemical BESs.

7 References

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