



– Deliverable D5.5 –

Viability of DVPPs

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Executive summary

In Task 5.2, a tool to optimize the bidding strategy of Dynamic Virtual Power Plants (DVPPs) when engaging in European energy and ancillary service markets was developed. The operation and performance of the proposed tool were discussed in Deliverable D5.2 through a comprehensive set of illustrative examples, demonstrating its effectiveness and applicability. Preliminary results showcased the flexibility of the robust DVPP optimization model, empowering users to define the uncertain range boundaries based on their preferred strategy, be it optimistic, neutral, or conservationist.

This report, which is the result of Task T5.5, presents and discusses more comprehensive economic viability studies of DVPPs for different synthetic, yet realistic, case studies defined in Task T5.4.

The aim is twofold. On the one hand, the model's simplicity and computational efficiency are demonstrated, showcasing its potential to scale effortlessly to systems of varying sizes, characteristics and complexities. On the other hand, a thorough evaluation of a diverse array of realistic scenarios, derived from actual European electricity market situations, is conducted using the proposed DVPP model. The DVPP model's versatility allows it to be readily applied to virtually any European country. However, to illustrate its effectiveness in specific regional contexts, two main examples are discussed in the document, namely a Southern-Europe region (Spain) and a Northern-Europe region (Denmark). By showcasing these contrasting scenarios, we demonstrate how the DVPP model can be tailored to diverse energy market conditions across Europe.

Through this comprehensive evaluation, valuable insights for potential DVPP operators to optimize their profits while participating in distinct electricity markets are proposed. The DVPP model's versatility enables users to make informed decisions based on their specific strategies, optimizing returns in both standard and novel market conditions. For instance, in the case of the Spanish scenarios, the results obtained from simulations indicate that properly configured and operated DVPPs can be economically more efficient than other solutions based on, e.g., electrochemical Battery Energy Storages (BESs) of several tens of megawatt-hour capacity. For instance, without coordinating the DVPP units, a 8 MW/16 MWh BES needs to be installed to achieve a similar performance than a nondispatchable source-based DVPP with an installed capacity of 200 MW. These promising findings provide valuable insights for DVPP operators, suggesting that the optimized DVPP configuration can outperform battery storage solutions in the contexts analyzed. Different scenarios of uncertainties on weather conditions are analyzed, for example sunny and cloudy days for the Southern-Europe region and windy and no-windy days for the Northern-Europe region.

The DVPP optimization tool proposed in D5.2 was primarily focused on optimizing daily bidding in electricity markets. It considered a fixed DVPP portfolio, where a predetermined set of units was aggregated as a single market participation entity. The model relied on short-term data and forecasting for daily operations, making it suitable for immediate market responses. While this approach provides valuable insights into the DVPP's performance and capabilities, it had some limitations. One major constraint was the lack of consideration for longer-term planning and strategic decision-making, i.e., the optimal configuration of a DVPP.

In this report, another enhancement to this DVPP model is proposed, where the focus is extended beyond optimizing daily bidding in electricity markets with a fixed DVPP portfolio. Instead, the updated model adopts a broader perspective, encompassing longer time horizons (e.g., several months).

With the ability to select a specific set of units to be aggregated as a single market participation entity, DVPP operators can proactively adapt their strategies to effectively capitalize on market dynamics and changing conditions. By considering extended time horizons, operators can better align their DVPP configuration with market trends, demand forecasts, and renewable energy availability, leading to maximized profitability and sustainable market participation.

This update to the DVPP model marks a significant advancement in the field, offering a comprehensive approach that addresses both short-term and long-term market challenges. By empowering operators with the flexibility to plan ahead for up to several months, the improved model greatly enhances decision-making capabilities and underscores its relevance as an invaluable tool for successful DVPP operations in the competitive European electricity markets.

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List of Abbreviations

BES	Battery Energy Storage
BIO	Biomass Power Plant
DAM	Day-Ahead Market
D-RES	Dispatchable Renewable Energy Source
DVPP	Dynamic Virtual Power Plant
ESS	Energy Storage System
FHPP	Flow-of-the-river Hydroelectric Power Plant
HPP	Hydroelectric Power Plant
HPPR	Hydroelectric Power Plant with Reservoir
IDM	Intra-Day Market
ND-RES	Non-dispatchable Renewable Energy Source
PCC	Point of Common Coupling
PV	Photo-voltaic
REE	Red Eléctrica de España
RES	Renewable Energy Source
SoC	State of Charge
SR	Secondary Reserve
SRM	Secondary Reserve Market
STU	Solar Thermal Unit
WP	Work Package
WPP	Wind Power Plant

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1 Introduction

1.1 Task 5.5 Overview

This report presents the outcomes of Task 5.5, focusing on extensive economic viability studies of Dynamic Virtual Power Plants (DVPPs) in diverse synthetic yet realistic case studies defined in Task T5.4. This DVPP economic viability hinges on factors such as available energy resources and chosen business models. The successful operation of a DVPP is closely linked to its configuration, encompassing the selection of Renewable Energy Sources (RESs) within the DVPP. The evaluation utilizes the DVPP optimization tool developed in Task 5.2 for their optimal bidding in European electricity markets. Through this tool, it is assessed which business models yield the most benefits, considering performance indices to gauge goal attainment and service provisions.

An essential focus of this task lies in determining the type and optimal size of dispatchable and nondispatchable RESs. Particular emphasis is placed on comparing DVPPs against solutions based on electrochemical battery energy storage systems.

1.2 Objectives and Outline of the Deliverable

The main objective of this document is to conduct in-depth economic viability studies of DVPPs based on real-world scenarios from two scenarios: one that emulates the situation in Southern-Europe regions (Spain), and another for a Northern-Europe country (Denmark). By analyzing the real-world cases of Spain and Denmark, valuable insights into the effectiveness of DVPPs in diverse energy market landscapes are obtained, providing a solid foundation for decision-making and practical implementation.

Additionally, we highlight a significant model update to the DVPP optimization framework, introducing a forward-looking approach to address long-term planning and strategic decision-making. By extending the time horizons of the model (e.g., up to several months), DVPP operators can proactively align their configurations with evolving market trends, demand forecasts, and renewable energy availability. This enhancement empowers operators to make informed decisions, ensuring the sustainability and competitiveness of DVPPs in the dynamic energy landscape.

1.3 Structure of the Deliverable

The remainder of this Deliverable is organized as follows.

Chapter 2 provides an improvement over the DVPP optimal operation tool proposed in D5.2. An update of the robust operation formulation is proposed to make mid and long-term optimal DVPP configuration decisions based on the DVPP maximum power limitation allowed by, e.g., regulatory agents, and a portfolio of available units for selection.

Chapter 3 evaluates this long-term DVPP optimal configuration upgrade by means of several case studies. Different scenarios are analyzed considering changes in portfolio availability, seasonal variations, uncertainty scenarios, and evaluated horizons.

A thorough evaluation of the economic viability of DVPPs in daily energy and ancillary markets is provided in Chapter 4. A comprehensive set of case studies and scenarios based on the definitions provided in D5.4 is defined, and an exhaustive collection of simulation results is presented and discussed. Remarks on the results obtained for each case study are also drawn.

Finally, Chapter 5 draws conclusions, and outlines the final work directions in the WP for Task T5.7.

2 Market Planning Model for Robust Optimal DVPP Configuration

This chapter expands upon the work detailed in Deliverable 5.2, extending the original robust operation formulation of a DVPP to accommodate mid and long-term forecasting. Furthermore, it lays out an optimal DVPP configuration scheme, which includes a maximum power limitation and a portfolio of available units. The updated model creates a representation of the operation and participation of the DVPP in Day-Ahead Market (DAM) considering phenomena that can be neglected in short-term representations. Firstly, an overview of the model is given in Section 2.1, then the nomenclature and formulation are explained in Section 2.2.

2.1 Overview

The model introduced in this chapter is a mixed-integer programming optimization algorithm that represents the operation of a DVPP which acts as a price-taker in the market. The aim of the model is to determine the optimal offers the DVPP should propose in the DAM and in the Secondary Reserve Markets (SRMs) (both up and down) across the studied horizon and the optimal DVPP configuration when size constraints are given.

To address uncertainties linked with the prices in the DAM and in both the SRM up and down, and the forecast for the maximum production of Non-dispatchable Renewable Energy Sources (ND-RESs) such as Photo-voltaic (PV), the model employs robust optimization techniques. The resources in this formulation are divided into four types, each with an specific set of constraints to model them:

1. Dispatchable Renewable Energy Source (D-RES): These resources can be dispatched based on demand and can represents resources such as Biomass Power Plant (BIO) or Hydroelectric Power Plant with Reservoir (HPPR).
2. ND-RES: These resources maximum production is not controllable because their operation depends on an hourly maximum production forecast. They typically include wind or solar resources, or Flow-of-the-River Hydroelectric Power Plant (FHPP).
3. Solar Thermal Unit (STU): This model is specifically designed for solar thermal units. Like ND-RES, they depend on an hourly maximum production forecast. However, STU manages both electrical and thermal energy and can be supplemented with thermal storage.
4. Energy Storage System (ESS): These models represent energy storage (mainly electrochemical-based units, such as batteries), which are capable of balancing generation and load, thereby improving the flexibility and reliability of the DVPP.
5. Flexible demand: This model represents loads able modifying their active power consumption, either for regulation or market purposes, or both.

Note that flexible demand is still usable in the model. However, for the sake of clarity and without loss of generality, flexible demands will not be considered when calculating the DVPP capacity. Therefore, DVPP size constraints do not affect these resources.

By integrating these diverse types of resources, the optimization model can accurately capture the dynamic and operation of a DVPP, thus facilitating decision-making under uncertain market conditions.

2.2 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, $\hat{A}$ ($\hat{A}$);
- 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 ESSs, $a^+, A^+, (a^-, A^-)$.

2.2.1 Indexes and sets

Symbol	Description
$c \in \mathcal{C}/\mathcal{C}_b$	Conventional, D-RESs/D-RESs connected to bus b
$r \in \mathcal{R}/\mathcal{R}_b$	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
$\theta \in \Theta/\Theta_b$	STUs / STUs connected to bus b
Ξ^{DA}	Set of decision variables of DAM

2.2.2 Parameters

Symbol	Description	Unit
$\bar{A}$	Maximum production by D-RES in the horizon	
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	[€]
$\underline{E}_{s,t}/\bar{E}_{s,t}$	Lower/upper bound of the energy stored in ESS s during time period t	[MWh]
$N_c^{\text{off}}/N_c^{\text{on}}$	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]
$\bar{O}$	Maximum numbers of units allowed for a DVPP	[-]
$\bar{P}_b$	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]
$\underline{P}_{d,t}/\bar{P}_{d,t}$	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]
$\underline{P}_s^+/\bar{P}_s^+$	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]
$\underline{P}_\theta^+/\bar{P}_\theta^+$	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]
$\underline{R}_c^0/\bar{R}_c^1$	Shut-down/start-up ramping limit of D-RES c	[MW/h]
$\underline{R}_c^{\text{SR}}/\bar{R}_c^{\text{SR}}$	Secondary reserve 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]
$\bar{W}$	Maximum power allowed for a DVPP	[MW]
Γ^{DA}	Uncertainty budget of DAM price	[-]
$\Gamma^{\text{SR},\uparrow}/\Gamma^{\text{SR},\downarrow}$	Uncertainty budget of up/down SRM price	[-]
Δt	Duration of time periods	[hour]
λ_t^{DA}	DAM price during time period t	[€/MWh]
$\lambda_t^{\text{SR},\uparrow}/\lambda_t^{\text{SR},\downarrow}$	SRM up/down price during time period t	[€/MW]

2.2.3 Continuous Variables

Symbol	Description	Unit
$e_{s,t}$	Energy stored in ESS s during time period t	[MWh]
p_t^{DA}	Total power traded in the DAM 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]
η_t^{DA}	Dual variable related to the uncertainty of the DAM price 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	[€]
$\sigma_s^{\text{SR},\uparrow} / \sigma_s^{\text{SR},\downarrow}$	Share of energy capacity of ESS s allocated to provide up/down secondary reserve	[%]
ν^{DA}	Dual variable related to the uncertainty of the DAM price	[€]
$\nu^{\text{SR},\uparrow} / \nu^{\text{SR},\downarrow}$	Dual variable related to the uncertainty of the up/down SRM price	[€]

2.2.4 Binary Variables

Symbol	Description	Unit
o_c	Binary variable that is 1 if D-RES c belongs to the VPP and 0 otherwise	[0/1]
o_r	Binary variable that is 1 if ND-RES c belongs to the VPP and 0 otherwise	[0/1]
o_θ	Binary variable that is 1 if STU c belongs to the VPP and 0 otherwise	[0/1]
o_s	Binary variable that is 1 if ESS c belongs to the VPP and 0 otherwise	[0/1]
$u_{c,t}$	Binary variable that is 1 if D-RES c is generating electricity during time period t , and 0 otherwise	[0/1]
$u_{s,t}$	Binary variable used to prevent the simultaneous charging and discharging of ESS s during time period t	[0/1]
$u_{\theta,t}$	Binary variable that is 1 if STU is generating electricity during time period t , and 0 otherwise	[0/1]
$u_{s,t}$	Binary variable that is 1 if ESS is offering electricity during time period t , and 0 otherwise	[0/1]

2.2.5 Overview of formulations across deliverables

Table 2-5 illustrates the modifications made in the model proposed in the present deliverable (D5.5) with respect to the models from earlier documents, namely Deliverables D5.1 and D5.2. The main modifications in the formulation concern the addition of constraints for the size of the DVPP, adaptations to not include available resources in the DVPP and new constraints to improve the long-term representation.

In the following sections, each of these modifications is detailed, providing the necessary adjustments to the mathematical formulation and describing how they contribute to the more robust and comprehensive operation of a DVPP.

Table 2-5 Mid and long-term planning formulation - Simultaneous DAM and SRM robust participation

Type	D5.1 Eq. Ref.	D5.2 Eq. Ref.	D5.5 Eq. Ref.
Objective Function		(3.2)	
Price Robustness Constraints		(3.4)	
Balancing Constraints	(4.4) – (4.9)		
Power Traded Constraints	(4.15) – (4.21)	(3.11)	
DVPP size limits			(2.2)
D-RES Constraints	(4.37) – (4.41); (4.43) – (4.43); (4.48) – (4.55)		(2.3)
ND-RES Constraints		(3.12)	(2.4)
Flexible Demand Constraints	(4.88) – (4.98)		
ESS Constraints	(4.110) – (4.126); (4.129) – (4.131)		(2.5)
STU	(4.146) – (4.169); (4.171) – (4.176); (4.201) – (4.206)	(3.15)	(2.6)
Network Constraints	(4.33) – (4.36)		

2.2.6 Objective function

In the formulation of the current deliverable, the objective function (2.1) used is inherited directly from Deliverable 5.2. The goal remains the same: to maximize the robust profit derived from the operation of units within the DVPP. This function takes into account the income generated from market participation, as well as costs related to each resource operation, and the robustness costs.

$$\begin{aligned}
 \max_{\Xi^{\text{DA}}} \sum_{t \in \mathcal{T}} & \left[\tilde{\lambda}_t^{\text{DA}} p_t^{\text{DA}} \Delta t + \tilde{\lambda}_t^{\text{SR}, \uparrow} r_t^{\text{SR}, \uparrow} + \tilde{\lambda}_t^{\text{SR}, \downarrow} r_t^{\text{SR}, \downarrow} \right. \\
 & \left. - \sum_{c \in \mathcal{C}} (C_c^V p_{c,t}^{\text{DA}} \Delta t + c_{c,t}^0 + c_{c,t}^1) - \sum_{r \in \mathcal{R}} C_r^M p_{r,t}^{\text{DA}} \Delta t \right] \\
 & - \sum_{s \in \mathcal{S}} c_s^{\text{deg}} - \sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}} C_{d,p} u_{d,p} \\
 & - \Gamma^{\text{DA}} \nu^{\text{DA}} - \Gamma^{\text{SR}, \uparrow} \nu^{\text{SR}, \uparrow} - \Gamma^{\text{SR}, \downarrow} \nu^{\text{SR}, \downarrow} - \sum_{t \in \mathcal{T}} \left(\eta_t^{\text{DA}} + \eta_t^{\text{SR}, \uparrow} + \eta_t^{\text{SR}, \downarrow} \right)
 \end{aligned} \tag{2.1}$$

2.2.7 Constraints

This section presents modifications to the constraints within the formulation to allow mid and long-term representation and DVPP configuration decision making. Firstly, a limit is placed on the number of units connected to the DVPP. Secondly, the maximum power output of the DVPP is constrained to align with realistic regulation. Thirdly, modifications for deactivating units not connected to the DVPP are made. Lastly, an extra constraint to improve the mid and long-term forecasting capabilities of the model is included

2.2.7.1 DVPP maximum size constraints

The eqs. (2.2) are included to limit the overall size of the DVPP in terms of the number of units and the total installed power. Equation (2.2a) limits the total number of units included in the DVPP. In this equation, the binary variables o_c , $o_{v,r}$, o_θ , and o_s denote the belonging of each unit to the DVPP. The sum of these variables is constrained to be less than or equal to $\bar{O}$, representing the maximum allowable number of units.

On the other hand, eq. (2.2b) restricts the total installed power of the DVPP. Here, $\bar{P}_c$, $\bar{P}_r$, $\bar{P}_\theta$, and $\bar{P}_s^-$ represent the power of each resource, including batteries discharging power. The sum of the power of the units included in the DVPP is constrained to be less than or equal to $\bar{W}$, representing the maximum allowable installed power.

By enforcing these constraints, the DVPP can adhere to its operational boundaries, ensuring that it does not exceed a given regulation. However, any of these constraints can be relaxed if just one of both criteria wants to be considered.

$$\sum_{c \in \mathcal{C}, r \in \mathcal{R}, \theta \in \Theta} o_c + o_{v,r} + o_\theta + o_s \leq \bar{O} \tag{2.2a}$$

$$\sum_{c \in \mathcal{C}, r \in \mathcal{R}, \theta \in \Theta} \bar{P}_c o_c + \bar{P}_r o_{v,r} + \bar{P}_\theta o_\theta + \bar{P}_s^- (1 - o_s) \leq \bar{W} \tag{2.2b}$$

2.2.7.2 D-RES constraints

Equations (2.3) represent the constraints related to the D-RES units that are part of the DVPP. Each equation has a specific role in limiting and controlling the operation of the D-RES units.

Equation (2.3a) ensures that a resource can only be committed during any time period ($u_{c,t} = 1$) if the resource belongs to the DVPP ($o_c = 1$). Equation (2.3b) limits the power output change of the D-RES units from one time period to the next one, whereas (2.3c) guarantees that the unit operation at the beginning of the studied horizon is coherent with its minimum on/off time. The difference between this constraints with respect to previous deliverables is that now when the D-RES does not belong to the DVPP both constraints are deactivated so it can be turned off since period one.

Finally, eq. (2.3d) limits the total energy that can be produced by each D-RES unit over the entire time horizon to be less than or equal to its maximum allowable energy generation, $\overline{A}_c$. This constraint, which can be neglected in the short term, is important for the mid and long-term operational planning, as it ensures that the total energy generated does not exceed the resource availability.

$$o_c \geq u_{c,t}, \quad \forall c \in \mathcal{C}, \forall t \in \mathcal{T} \quad (2.3a)$$

$$\begin{aligned} & \left(p_{c,(t-1)} + r_{v',c,(t-1)}^{\text{SR},\uparrow} \right) - \left(p_{c,t} - r_{v,c,t}^{\text{SR},\downarrow} \right) \\ & \leq \left(\underline{R}_c u_{c,t} + R_c^0 v_{c,t}^0 \right) \Delta t + \bar{P}_c o_c \end{aligned} \quad \forall v \geq 1, \forall v' \geq 1, \forall c \in \mathcal{C}, \forall t \in \mathcal{T} \quad (2.3b)$$

$$\sum_{t=1}^{N_c^{On}} (1 - u_{c,t}) = (1 - o_c) N_c^{On}, \quad \forall c \in \mathcal{C} \quad (2.3c)$$

$$\sum_{t=1}^T (p_{c,t} + r_{v,c,t}^{\text{SR},\uparrow}) \leq \overline{A}_c, \quad \forall v \geq 1, \quad \forall c \in \mathcal{C} \quad (2.3d)$$

2.2.7.3 ND-RES constraints

In previous model formulations, the production of ND-RESs was already adequately constrained; therefore, adding extra constraints is unnecessary to represent the mid and long-term operation. Besides, since ND-RES modelling does not consider up/down ramping or minimum production levels, modifying these constraints is not required when a unit is not included in the DVPP. Thus, only eq. (2.4) needs to be added in order to ensure that a resource can only be committed during any time period ($u_{r,t} = 1$) if the resource belongs to the DVPP ($o_r = 1$).

$$o_{v,r} \geq u_{v,r,t}, \quad \forall v \geq 1, \forall r \in \mathcal{R}, \forall t \in \mathcal{T} \quad (2.4)$$

2.2.7.4 ESS constraints

Equations (2.5) introduce the constraints related to the ESS units in the DVPP. These equations are critical for managing the ESS operational status and energy levels.

Constraint (2.5a) ensures that a resource can only be committed during any time period ($u_{s,t} = 1$) if the resource belongs to the DVPP ($o_s = 1$). The forthcoming equations, (2.5b) and (2.5c), guarantee that the stored energy level for each ESS unit remains within its capacity limits at the termination of the time horizon (at time $t = T$). On the other hand, eq. (2.5d) ensures the same within the examined horizon. The presented versions of these constraints allow a relaxation of the power limits of the ESS when it is not incorporated within the DVPP.

$$o_s \geq u_{s,t}, \quad \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (2.5a)$$

$$\underline{\alpha}_s (\underline{E}_s + \sigma_s^{\text{SR},\uparrow} (\bar{E}_s - \underline{E}_s)) \leq \bar{E}_s o_s + e_{s,t}, \quad \forall s \in \mathcal{S}, t = T \quad (2.5b)$$

$$e_{s,t} \leq \bar{E}_s o_s + \bar{\alpha}_s (\bar{E}_s - \sigma_s^{\text{SR},\downarrow} (\bar{E}_s - \underline{E}_s)) \quad \forall s \in \mathcal{S}, t = T \quad (2.5c)$$

$$\underline{E}_s (1 - o_s) + \sigma_s^{\text{SR},\uparrow} (\bar{E}_s - \underline{E}_s) \leq e_{s,t} \leq \bar{E}_s - \sigma_s^{\text{SR},\downarrow} (\bar{E}_s - \underline{E}_s) \quad \forall s \in \mathcal{S}, \forall t \leq T - 1 \quad (2.5d)$$

2.2.7.5 STU constraints

Finally, Constraints (2.6) apply to the STU within DVPP. Equation (2.6a) ensures that the STU can only be committed during any time period ($u_{\theta,t} = 1$) if it belongs to the DVPP ($o_\theta = 1$). Constraint (2.6b) enforces the minimum operation periods at beginning of the studied horizon. Again, when the STU does not belong to the DVPP this constraints is relaxed so it can be turned off in first period.

$$o_\theta \geq u_{\theta,t} \quad \forall \theta \in \Theta, \forall t \in \mathcal{T} \quad (2.6a)$$

$$\sum_{t=1}^{N_{k,\theta}^{\text{on}}} (1 - u_{\theta,t}) = (1 - o_\theta) N_{k,\theta}^{\text{on}} \quad \forall k \in \mathcal{K}, \forall \theta \in \Theta \quad (2.6b)$$

3 Viability Analysis of Different DVPP Configurations in Planning Studies

This section delves into the long-term viability model for the DVPP through several case studies. Initially, it introduces in Section 3.1 the chosen input data, explaining its relevance and contribution to the objectives of the report.

Then, various case studies are defined to assess the model's applicability under various conditions. These include changes in portfolio availability, seasonal variations, uncertainty scenarios, and horizon reduction. These studies gauge the model's resilience and evaluate the effects of distinct variables on the profitability of the DVPP. The results obtained from these case studies, presented and discussed in Section 3.2, showcase the efficiency and robustness of the model. Outcomes provide valuable insights into the ability of the model to successfully navigate various market conditions and uncertainties, effectively managing a variety of resources.

3.1 Data

This Section collects the main techno-economic data related to the set of units available to the planning problem to potentially conform the DVPP. These include, e.g., active power capacities, operation costs and time series of uncertain profiles (stochastic renewable sources and electricity market prices prices).

3.1.1 Unit Availability and System topology

Since the impact of the DVPP *subnetwork* topology is not the focus of this section, the electric grid is modelled as a two-node system for simplicity. One node represents the interconnection with the electrical system, and the second node encapsulates all generation units. As a result, constraints linked to the transmission system's limitations are omitted in this analysis.

Southern-Europe Network

Table 3-1 illustrates the units available for constructing the DVPP within the context of the Southern-European Network, and lists their corresponding power capacities and operation costs. The selection of these units and their parameters are influenced by the distinct characteristics of the region (Spain).

The ND-RES model requires the maximum hourly production series, capturing the resource availability for each respective unit. These include wind and solar power, as well as water flow for FHPP. The process of establishing these profiles is convoluted, since series do not solely represent the units' performance across the forecast horizon, but also encapsulate the uncertainty inherent in a realistic decision-making situation.

Table 3-1 DVPP units capacity and operation cost

DVPP resource	Capacity [MW]	Operation cost [€/MWh]
HPPR	40	7.5
BIO	10	23
WPP1	50	10
WPP2	50	7
WPP3	50	4
PV1	50	5
PV2	50	5
PV3	50	8
FHPP	40	7.5
STU	50	15

Maximum production series for PV, Wind Power Plant (WPP), and STU are obtained based on real utilization series from diverse provinces in Spain. Analogously, the FHPP maximum capacity was obtained in coherence with the measured flow of a Spanish river. Table 3-2 correlates each unit with its corresponding reference series, denoting which series are used to model each unit's performance and uncertainty.

Table 3-2 Reference series for each DVPP Unit

Resource	Reference series
WPP1	Almería wind production
WPP2	Granada wind production
WPP3	Málaga wind production
PV1	Jaen solar production
PV2	Almería solar production
PV3	Granada solar production
FHPP	Guadalimar river flow
STU	Málaga solar production

Figure 3-1 provides a graphical representation of historical daily utilization (i.e., the ratio between power production available and installed capacity) for the days used in the summer case studies (June, July, August of years 2014 through 2022). While only the solar generation in Málaga, Spain, is shown in this document, series for other locations have been similarly obtained.

Upon collecting and analyzing these series, the year 2018 has been selected to create the case studies and scenarios due to its balanced resource availability. This choice ensures a realistic and diverse representation for the modelling of the renewable units in the DVPP. Hourly data for wind and solar units were obtained from RED ELÉCTRICA ([1] and [2]), while hourly flows for the Guadalimar river were obtained from Spanish Government [3].

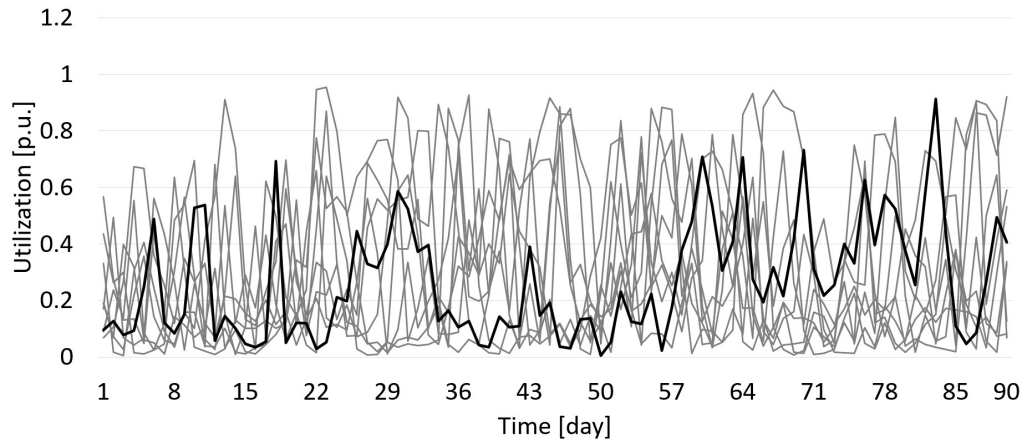


Figure 3-1 Historical daily utilization for the solar generation in Málaga, Spain during the months of June, July and August from 2014 to 2022. 2018 series highlighted in black

The dataset employed in our analysis encompasses time-series data from 2014 to 2022. The required deviation for the model, which is instrumental in representing forecast uncertainty, is computed as the difference between the chosen series and the hourly average of the three lowest values for each hour. Figure 3-2 presents the daily average negative deviations for the Málaga solar production for the first 90 days of 2018 as a percentage of the hourly value.

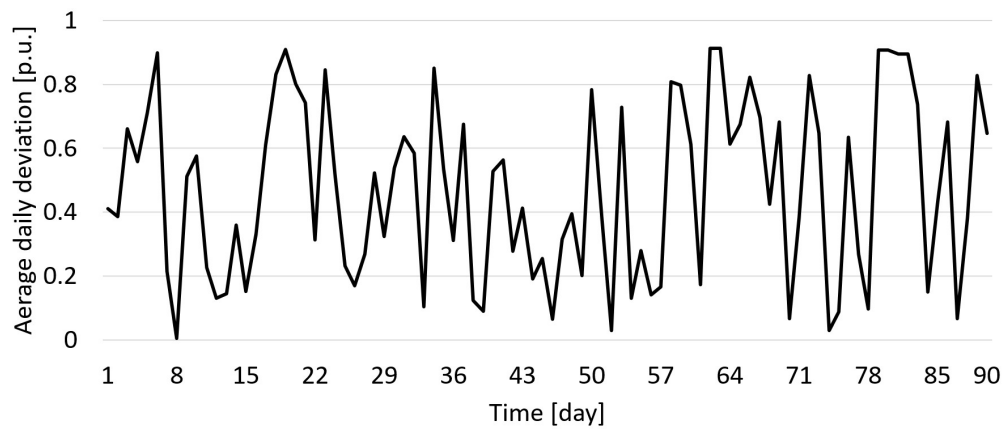


Figure 3-2 Negative deviation of the Málaga solar production series in summer 2018

The D-RES resources are straightforward to model. Their availability is limited by a constraint of maximum production over the operational horizon. Specifically, the BIO availability is dictated by the amount of bio-compost, while the HPPR availability depends on the volume of water in the reservoir and inflow rates. Table 3-3 shows these values.

Table 3-3 Resources availability for D-RES units

DVPP Unit	Maximum production [GWh]
HPPR	90% of FHPP available energy in the horizon
BIO	21 x day

While the availability of Biomass raw material is fixed as constant per day, the available water in the HPPR is calculated as a 90% of the maximum production by the flow of the river power plant in the simulated period.

3.1.2 Electricity Market Prices

The price values and deviations for the DAM, SRM up, and SRM down have been sourced and processed following the same methodology as that employed for the utilization series, explained in section 3.1.1. The data utilized for these calculations was obtained from RED ELÉCTRICA ([1] and [2]) and spans the years from 2014 to 2022. This methodology aims to capture the price trends and fluctuations, providing representative inputs for the optimization model and fostering more accurate and realistic simulations of the DVPP portfolio decision making.

3.2 Simulation results

In this section, the functionality of the proposed model will be demonstrated using a scenario based on Spain's summer of 2018 (June, July, August). The primary goal is to determine the optimal DVPP portfolio under a power limitation of 250MW. Section 3.2.1 commences by identifying an appropriate robustness budget for the simulation. Following this, Section 3.2.2 delves into the advantages of coordinating both ND-RES and D-RES within a DVPP framework. Subsequently, Section 3.2.3 considers the potential inclusion of HPP within the portfolio. The role and impact of including a STU are subsequently scrutinized in Section 3.2.4. Finally, Section 3.2.5 offers additional insight on other relevant aspects, such as problem-solving times and the influence of the selected scenario on the results.

3.2.1 Robustness analysis

This section conducts several parametric studies on the robust budget across four distinct scenarios:

- **Parametric on price forecast:** This study alters the robust budget for price in the DAM for a DVPP of 250 MW, formed by the optimal combination of ND-RES units listed in Table 3-4.
- **Parametric on solar forecast:** This study modifies the robust budget for the solar forecast for a DVPP created by the aggregation of the solar photovoltaic plants listed in Table 3-4.
- **Parametric on wind forecast:** In this study, the robust budget for the wind forecast is varied for a DVPP constituted by the combination of wind plants indicated in Table 3-4.
- **Complete parametric:** This scenario alters the robust budget for the wind forecast, solar forecast, price in the DAM for the 250 MW optimal DVPP, composed of units enumerated in Table 3-4.

Table 3-4 specifies the units available for composing the DVPP in these parametric cases. Subsequently, the impact on the profit of the DVPP of the robust budget's parametric for every study is presented in Fig. 3-3.

Table 3-4 Units available to conform the DVPP in the parametric cases

Unit	Parametric on price	Parametric on solar	Parametric on wind	Complete parametric
BIO	-	-	-	✓
WPP1	✓	-	✓	✓
WPP2	✓	-	✓	✓
WPP3	✓	-	✓	✓
PV1	✓	✓	-	✓
PV2	✓	✓	-	✓
PV3	✓	✓	-	✓

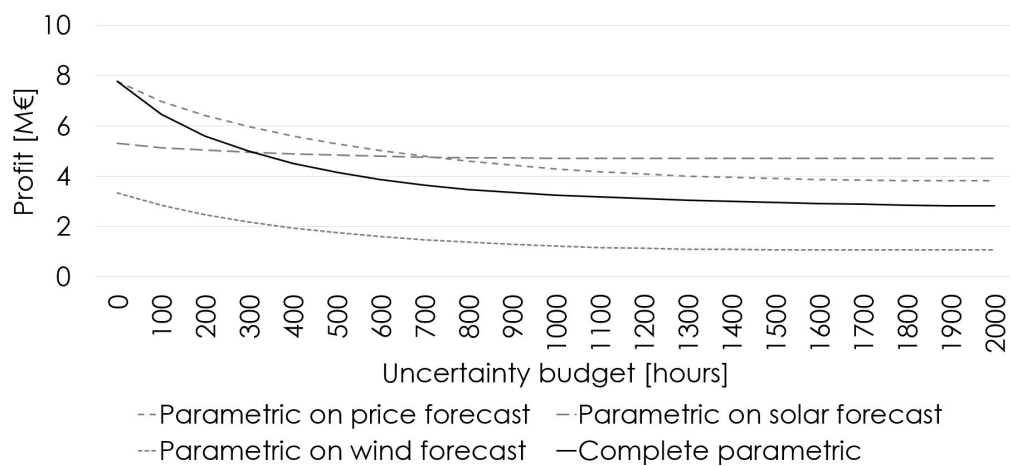


Figure 3-3 Parametric study of the robust budget for prices and renewable availability

By studying the profitability against the robust budget in Fig. 3-3, it can be observed that profitability reduces as the robust budget increases. The decline in profitability is due to the increasing caution exercised in the planning and operation of the DVPP, which in turn restricts the potential for higher returns. This trend is consistent across all parametric scenarios, as well as with the sensitivity analysis carried out to validate the daily optimal DVPP market participation tool proposed in Deliverable D5.2.

In the parametric on price study, an increase in the robust budget leads to a decline in profitability from 7.75 M€ to 3.82 M€. This indicates the sensitivity of profits to price fluctuations. A higher budget implies a more conservative approach in the energy market price forecasts (DAM), reducing potential profit-making.

In the parametrics over the solar wind forecast, the profitability also reduces as the robust budget increases. However, the profitability under the Parametric solar scenario is relatively higher than the parametric wind scenario although the DVPP is the 150 MW in both cases. This difference could be attributed to the studied scenario, which correspond to a summer situation in Spain; therefore, solar energy production is expected to be high. Additionally, it can be noticed that the profit from the parametric on solar forecast remains consistent for robust budgets exceeding 1000 hours. This stability is a consequence of the fact that solar power production during night hours is invariably forecasted as zero in optimistic and pessimistic scenarios, a predictability inherent to the nature of solar energy.

The complete parametric study, where the robust budget is applied to all uncertainties, presents a similar trend of declining profitability. Consequently, it yields to a less risk-prone DVPP operation. The scenario starts with a profit of 7.78 M€ at a robust budget of 0, and ends with a profit of 2.83 M€ at a robust budget of 2000 hours, a 63.62% reduction.

In coherence with these results, a robust budget value of 336 hours for prices and energy forecast is set in the rest of the executions of chapter 3. Representing a balanced scenario finding an equilibrium between profit maximization and risk mitigation. It allows the DVPP to adapt to the equivalent time of two weeks of robust values, a reasonable buffer for managing market and forecast uncertainties.

3.2.2 Comparison: Independent Units vs. DVPP

This section evaluates the impact of coordinating D-RES and ND-RES in a DVPP. We initiate the study by examining resources without coordination, then proceed to the aggregation of only ND-RES in a DVPP, and finally, we consider the integration of both ND-RES and D-RES in a DVPP. The units under examination in this section are listed in Table 3-5.

Table 3-5 Units studied independently and as a DVPP

Unit	No coordination	ND-RES DVPP	ND-RES and D-RES DVPP
BIO	✓	-	✓
WPP1	✓	✓	✓
WPP2	✓	✓	✓
WPP3	✓	✓	✓
PV1	✓	✓	✓
PV2	✓	✓	✓
PV3	✓	✓	✓

Table 3-6 presents the individual performance metrics - profit, income, cost, power, and generation - for each resource operating independently, along with the aggregated results of all units operating without coordination.

Table 3-6 Independent units profit, income, cost, power and generation

Unit	Profit [M€]	Income [M€]	Operation cost [M€]	Power [MW]	Generation [GWh]
BIO	0.63	1.09	0.46	10	20
WPP1	0.41	0.52	0.1	50	10.48
WPP2	0.51	0.6	0.09	50	12.25
WPP3	0.52	0.57	0.05	50	12.38
PV1	1.19	1.32	0.14	50	27.54
PV2	1.08	1.21	0.13	50	25.59
PV3	1.16	1.38	0.23	50	28.39
Total	5.5	6.69	1.19	310	136.63

In Table 3-7, we examine the economic and operational performance of a 250 MW ND-RES-based DVPP, composed of the optimal available units. The table also shows the performance metrics for the units of the DVPP operating with no coordination. Furthermore, it can be observed that the profitability of the resources increases when coordinated in a DVPP although the operation costs barely rises.

Table 3-7 ND-RES DVPP, income, cost, power and generation

Portfolio	Profit [M€]	Income [M€]	Operation cost [M€]	Power [MW]	Generation [GWh]
No coord.	4.46	5.08	0.63	250	106.15
ND-RES DVPP	4.72	5.35	0.63	250	107.24
Difference [%]	5.82	5.35	0.02	0	1.03

Table 3-8 further delves into the operational details of the units coordinated in the optimal 250 MW ND-RES DVPP, providing an in-depth understanding of the DVPP operation. Note that the only ND-RES that does not belong to the DVPP is the WPP1.

Table 3-8 ND-RES DVPP optimal configuration

Variable		WPP2	WPP3	PV1	PV2	PV3
Cost	[M€]	0.09	0.05	0.14	0.13	0.21
Generation	[GWh]	12.63	13.48	27.92	26.47	26.74
Utl. factor	[%]	11.43	12.21	25.28	23.97	24.21
Commitment	[h]	1537	1570	1029	1053	1045
Start-ups	[-]	140	97	99	96	130
Shut-downs	[-]	139	96	99	96	130

Table 3-9 illustrates the economic and operational metrics of an optimal 250 MW DVPP consisting of both ND-RES and D-RES. In these cases the portfolio of the optimal DVPP consist on BIO, WPP1, WPP2, WPP3, PV1, PV2 and PV3, with a total power of 210 MW. The table also presents the metrics for the aggregation of these resources with no coordination. The lower part of the table provides a percentage comparison between the DVPP and the aggregated performance of all D-RES and ND-RES of the DVPP operating without coordination. As expected the integration of resources into a DVPP enhances the overall profitability.

Table 3-9 DVPP from D-RES and ND-RES, income, cost, power and generation

Portfolio	Profit [M€]	Income [M€]	Operation cost [M€]	Power [MW]	Generation [GWh]
No coord.	4.58	5.57	1	210	113.9
D-RES DVPP	4.81	5.82	1	210	114.75
Difference [%]	4.78	4.29	0.02	0	0.74

These results suggests that the maximum power of the resource is not an indicator to estimate whether a resource should be included in the DVPP, as in this situation is preferable to have a D-RES of 10MW and establishing a smaller DVPP than including a ND-RES of 50MW capacity.

Table 3-10 illustrates the operation of each resource in the DVPP, demonstrating each unit's operation cost, power generation, utilization efficiency, commitment duration, and frequency of start-ups and shutdowns. The BIO appears to be the most utilized in terms of time, generating as much as allowed by the input data, yet it incurs the highest operational costs. Conversely, the WPP3 unit has the least generation, due to the availability of wind power. The three Solar units exhibit similar performance, with frequent cycling on and off, and they contribute a substantial portion to the total power generation.

Table 3-10 D-RES and ND-RES optimal DVPP configuration

Variable		BIO	WPP3	PV1	PV2	PV3
Cost	[M€]	0.46	0.05	0.14	0.13	0.22
Generation	[GWh]	19.98	13.48	27.94	26.39	26.95
Utl. factor	[%]	90.46	12.21	25.3	23.9	24.4
Commitment	[h]	2039	1570	1029	1048	1062
Start-ups	[-]	20	97	99	101	128
Shut-downs	[-]	19	96	99	101	128

Figure 3-4 presents the weekly energy generation within the DVPP. ND-RES generation is consistently superior than D-RES generation, primarily due to the constitution of the DVPP. While the production levels remain relatively consistent across different weeks, noticeable variations can be detected. Specifically, the production during the first week of June and the last week of August is lower than the rest of the summer. This fluctuation can likely be attributed to the changes in solar radiation during these periods.

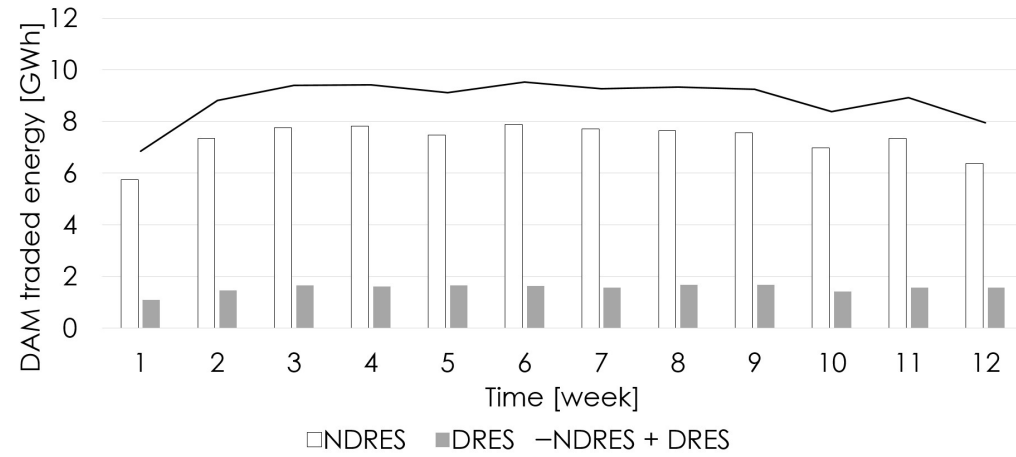


Figure 3-4 Weekly energy traded in the DAM generated by D-RES and ND-RES

Figure 3-5 helps to understand the operation of the DVPP. During the day hours ND-RES generation is higher, mainly due to the solar generation. During night hours D-RES produce, since they can produce on demand.

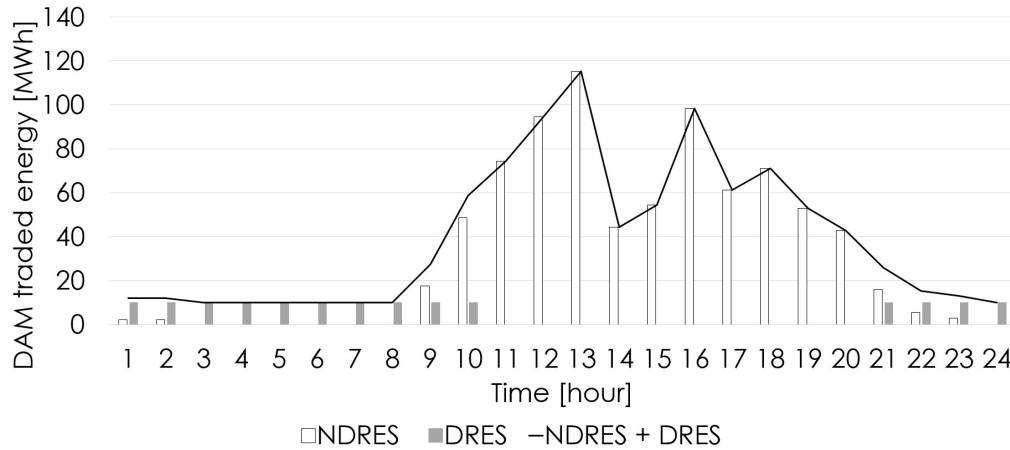


Figure 3-5 Hourly energy traded in the DAM generated by D-RES and ND-RES during a day period

3.2.3 Introducing HPP

This section explores the inclusion of hydraulic resources in the optimal configuration of the DVPP. Two types of HPP are considered: HPPR, a hydraulic power plant with a reservoir modeled as D-RES, and FHPP, a flow-of-the-river unit modeled as a ND-RES.

Table 3-11 Available portfolios

Unit	Base case	HPPR only	FHPP only	Both HPP
BIO	✓	✓	✓	✓
HPPR	-	✓	-	✓
FHPP	-	-	✓	✓
WPP1	✓	✓	✓	✓
WPP2	✓	✓	✓	✓
WPP3	✓	✓	✓	✓
PV1	✓	✓	✓	✓
PV2	✓	✓	✓	✓
PV3	✓	✓	✓	✓

The DVPP is expanded from its original 210 MW configuration (Base case), calculated in subsection 3.2.2, to include these HPP, either separately (HPPR only, FHPP only) or combined (Both HPP units).

Table 3-12 presents the performance metrics of the different DVPP configurations. Notably, the inclusion of both types of HPP improves the DVPP profitability. The highest profit (6.12 M€) is achieved when both HPP are included in the DVPP. Although the power capacity doesn't reach the maximum allowed capacity of 250 MW for the DVPP, when both HPP are included the generation increases a 20.13%, the operational cost a 22% and the profit a 27.23% respect the base case.

Table 3-12 DVPP configurations with HPP available: income, cost, power and generation

Scenario	Profit [M€]	Income [M€]	Operation cost [M€]	Power [MW]	Generation [GWh]
Base case	4.81	5.82	1	210	114.75
HPPR	5.97	7.12	1.15	250	134.12
FHPP	5.62	6.75	1.13	250	131.45
Both HPP	6.12	7.34	1.22	240	137.85

The Tables 3-10, 3-13, 3-14, and 3-15 detail the operation of the units for each scenario. It's interesting to see that the inclusion of hydro resources barely changes the commitment and utilization factor of other units.

Table 3-10, presented in subsection 3.2.2, provides an overview of the operational parameters for the scenario Base Cases configuration, where no HPP are included. This configuration includes BIO, one type of WPP (WPP3), and three types of solar photovoltaic resources (PV1, PV2, and PV3). In terms of cost and generation, solar power resources contribute significantly, while wind turbines show higher commitment time with lower utilization factor.

Table 3-13 presents the operation details of the DVPP when HPPR is included. In this cases it is optimal to include HPPR in the DVPP. Since the maximum capacity of the DVPP is set as 250 MW and the previous optimal configuration was of 210 MW, the resource HPPR can be included without excluding the previous portfolio. It is remarkable that HPPR presents the smallest commitment time, since this unit can produce on demand the model finds a better strategy to produce at maximum capacity during the more profitable hours than split the generation in the horizon, results show that during a 75.26% of the time committed the HPPR is producing at maximum capacity.

Table 3-13 HPPR-only optimal configuration

Variable		BIO	HPPR	WPP3	PV1	PV2	PV3
Cost	[M€]	0.46	0.15	0.05	0.14	0.13	0.22
Generation	[GWh]	19.98	19.33	13.48	28.1	26.25	26.98
Utl. factor	[%]	90.47	21.88	12.21	25.44	23.77	24.42
Commitment	[h]	2039	574	1570	1026	1049	1065
Start-ups	[-]	20	61	97	100	98	125
Shut-downs	[-]	19	61	96	100	98	125

Table 3-14 showcases the optimal configuration when FHPP, a flow-of-the-river unit, is included in the DVPP. As in the previous case, it is not necessary to exclude any resource from the Base Case portfolio. The commitment time of the FHPP is noticeably higher than the obtained in the previous cases for HPPR this is because FHPP cannot operate on demand and has to utilize the continuous river flow instantaneously.

Table 3-14 FHPP-only optimal configuration

Variable		BIO	WPP3	PV1	PV2	PV3	FHPP
Cost	[M€]	0.46	0.05	0.14	0.13	0.22	0.12
Generation	[GWh]	20	13.48	28.3	26.32	26.89	16.46
Utl. factor	[%]	90.52	12.21	25.63	23.83	24.35	18.63
Commitment	[h]	2047	1570	1033	1051	1059	2132
Start-ups	[-]	19	97	95	98	130	32
Shut-downs	[-]	18	96	95	98	130	31

Lastly, Table 3-15 illustrates the operational details of the DVPP when both HPP, HPPR and FHPP, are included. This time, to include both hydraulic power plants WPP3 was excluded to fulfill the maximum power limitation. This portfolio leads to the most profitable DVPP configuration so far. Both HPP maintain comparable operational behavior to when they are included individually in the DVPP.

Table 3-15 Both HPP case optimal configuration

Variable		BIO	HPPR	PV1	PV2	PV3	FHPP
Cost	[M€]	0.46	0.15	0.14	0.13	0.22	0.12
Generation	[GWh]	20	19.33	28.25	26.72	27.05	16.51
Utl. factor	[%]	90.54	21.88	25.58	24.19	24.49	18.68
Commitment	[h]	2051	576	1033	1055	1064	2135
Start-ups	[-]	19	60	95	94	126	29
Shut-downs	[-]	18	60	95	94	126	28

In all cases, the inclusion of both types of HPP provides benefits, enhancing the DVPP profitability and operational flexibility.

3.2.4 Introducing STU

In this section, the Base Case considered is the optimal DVPP that consists of ND-RES, D-RES, and the two HPPs summarized in Table 3-15. Here, the focus shifts to examining the impact of incorporating a Solar Thermal Unit (STU) into the portfolio, which enters into the optimal DVPP portfolio, replacing the FHPP of the Base Case.

As shown in Table 3-16, the introduction of an STU provides a noticeable increase in both the profit and generation of the DVPP, with profit rising from 6.12 M€ in the base case to 6.34 M€ in the STU-integrated scenario. The total generation also increases, from 137.85 GWh to 147.91 GWh, maximizing the use of the imposed 250 MW power limit.

Table 3-16 DVPP with STU profit, income, cost, power and generation

Portfolio	Profit [M€]	Income [M€]	Operation cost [M€]	Power [MW]	Generation [GWh]
Base Case	6.12	7.34	1.22	240	137.85
DVPP with STU	6.34	7.83	1.49	250	147.91
Difference [%]	3.59	6.67	22.13	4.16	7.29

Table 3-17 further details the optimal configuration when an STU is incorporated into the DVPP. The STU contributes a generation of 25.73 GWh at a cost of 0.39 M€, operating with a utilization factor of 23.3%. Despite its limited commitment time (709 hours) compared to other units, the STU provides a profitable contribution to the DVPP operation. The complexity of managing starts and shutdowns in a STU modelled, with longer on and off operation times results in less start-ups and shut-downs. Therefore, including an STU in the DVPP portfolio can be an effective strategy to increase profitability.

Table 3-17 DVPP with available STU optimal configuration

Variable		BIO	HPPR	PV1	PV2	PV3	STU
Cost	[M€]	0.46	0.15	0.14	0.13	0.22	0.39
Generation	[GWh]	20	19.33	28.67	26.68	27.5	25.73
Utl. factor	[%]	90.54	21.88	25.96	24.16	24.89	23.3
Commitment	[h]	2063	578	1034	1056	1090	709
Start-ups	[-]	16	60	94	93	118	46
Shut-downs	[-]	15	60	94	93	118	46

3.2.5 Other scenarios

3.2.5.1 Shorter period forecast

In this analysis, the DVPP, composed by ND-RES, D-RES, and HPP summarized in Table 3-15, is assessed over a shorter horizon, limited to the month of July 2018 only. This more specific scenario aims to evaluate the model's performance under a restricted time frame.

As depicted in Table 3-18, the one-month scenario yields a profit of 1.87 M€, an income of 2.28 M€, and an operational cost of 0.4 M€. This optimal DVPP scenario match the obtained in the base case, resulting in a generation of 45.34 GWh. The stark difference in values, when compared to the three-month planning problem, is attributable to the reduced operational period.

Table 3-18 One-month horizon comparison, income, cost, power and generation

Planning horizon	Profit [M€]	Income [M€]	Operation cost [M€]	Power [MW]	Generation [GWh]
Three-month	6.12	7.34	1.22	240	137.85
One-month	1.87	2.28	0.4	240	45.34
Difference [%]	-69.44	-68.93	-67.22	0	-67.11

While this shorter-term scenario doesn't offer significant new insights compared to the base case, it effectively demonstrates the model's flexibility and scalability. The results remain consistent, confirming the model's robust functionality and its ability to generate accurate solutions over varying time horizons.

3.2.5.2 Winter period

In this analysis, the operation of the DVPP is examined during a three-month winter period, specifically January, February, and March. Data is based in 2018. This scenario presents an interesting alteration in the optimal DVPP portfolio, where the model excludes PVs and adds WPPs.

As shown in Table 3-19, the winter scenario delivers a profit of 3.72 M€, an income of 4.79 M€, and operational costs amounting to 1.07 M€. The power output of the DVPP reaches the increased limit of 250 MW, generating 111.82 GWh over the period. The decrease in comparison with the summer case is due to the scarcity of solar generation in winter.

Table 3-19 Winter scenario comparison, income, cost, power and generation

Season	Profit [M€]	Income [M€]	Operation cost [M€]	Power [MW]	Generation [GWh]
Summer	6.12	7.34	1.22	240	137.85
Winter	3.72	4.79	1.07	250	111.82
Difference [%]	-39.21	-34.74	-12.29	4.16	-18.88

The optimal DVPP configuration for this winter scenario is presented in Table 3-20. Noticeably, the portfolio now includes three WPP (WPP1, WPP2, WPP3) while retaining the BIO and HPP. Interestingly, only one solar field (PV1) remains, reflecting the reduced solar resources available during the winter months.

Table 3-20 Winter scenario optimal configuration

Variable		BIO	HPPR	WPP1	WPP2	WPP3	PV1
Cost	[M€]	0.42	0.05	0.26	0.17	0.07	0.09
Generation	[GWh]	18.35	6.93	25.62	24.76	17.98	18.19
Utl. factor	[%]	83.05	7.85	23.19	22.41	16.28	16.47
Commitment	[h]	1950	280	1512	1784	1669	1407
Start-ups	[-]	18	52	146	92	105	355
Shut-downs	[-]	17	52	146	91	104	355

The BIO unit continues to present high utilization and commitment, but the WPP show a higher level of starts and shutdowns due to their dependency on fluctuating wind resources. The reduced commitment of PV1 aligns with expectations given the decreased solar irradiation during winter.

Overall, these results demonstrate the model's dynamic capability to adapt to different seasonal conditions by adjusting the optimal DVPP composition, reflecting the varying generation profiles of different renewable energy sources throughout the year.

3.2.5.3 Analysis of Computational Burden

The computational performance of the DVPP model was evaluated on a desktop computer equipped with an Intel(R) Core(TM) i7-8700 CPU operating at 3.20GHz, 64GB RAM, and running on Windows 11 Enterprise version 22H2. The run times for different portfolio configurations are given below:

- Single D-RES: 26 seconds
- Single ND-RES: 17 seconds
- Six ND-RES: 18 seconds
- Six ND-RES and one D-RES: 31 seconds
- Six ND-RES, one ND-RES and one STU: 33 minutes

These results indicate that the model can efficiently solve configurations with ND-RES and D-RES in under a minute. However, when the portfolio becomes more complex, particularly including STU, the solving time increases significantly due to the extra variables require, e.g., piece-wise linearizations. Considering the planning horizons of the scenarios discussed in this Chapter, the problem still remains within manageable limits for a detailed simulation.

3.3 Concluding Remarks

The case studies explored in this section showcase the flexibility and adaptability of the model in determining the optimal DVPP portfolio under various conditions. From the seasonal variations in energy availability to the introduction of different power resources types and power limitations, the model consistently demonstrated its ability to adjust and select the most profitable portfolio.

Regarding computational performance, the model exhibits manageable solving times, an essential feature for its practical use in real-world applications. This computational efficiency allows the model to evaluate a large set of options and quickly determine the optimal configuration, a crucial aspect when dealing with volatile energy markets and variable renewable resources.

In summary, the results demonstrate the model's successful achievement of its primary objective: to determine the optimal and most profitable portfolio for a DVPP, taking into account the inherent complexities and variability of renewable energy sources. The demonstrated flexibility and satisfactory performance under varying conditions suggest that this model could be a valuable tool for decision-making in the energy sector.

4 Analysis of Business Cases for DVPP Market Participation Viability

In this chapter, the economic viability of renewable-based DVPPs participating in energy and ancillary service markets will be thoroughly studied. With this aim a comprehensive set of case studies and scenarios based on those proposed in Deliverable D5.4 is created to analyze the profits that DVPPs can make from such market participation under a large variety of conditions.

The chapter is organized as follows. The data used as input for the different case studies is discussed in Section 4.1. Section 4.2 presents the different case studies and scenarios considered. Results from such scenarios and cases are shown and discussed in Section 4.3.

4.1 Data

In this Section, the different data used to characterize all cases and scenarios are presented. These data include network topologies and DVPP portfolio configurations; capacities, costs and other techno-economic data of DVPP units; and uncertainty profiles such as prices and energy sources.

4.1.1 System Topologies and Units

In this section, different system topologies are considered to represent DVPP for both Southern-Europe Network and Northern-Europe Network. The DVPP units in each network are defined accordingly to represent the most prevalent units that are used in Southern-Europe or Northern-Europe countries for different weather conditions.

Southern-Europe Network

The DVPP considered in this Section is adopted from Deliverable D5.1 and is shown in Fig. 4-1. The DVPP is distributed across a 12-node network connected to the main grid through a Point of Common Coupling (PCC). The network is a representation of a southern-Spanish region. Not all units in the network are part of the DVPP as it mirrors what could occur in reality. The DVPP consists of two D-REs (hydro plant at bus 6 and biomass plant at bus 9), three ND-REs (wind farm at bus 4, solar PV1 at bus 8, and solar PV2 at bus 11), an STU (bus 1), and three flexible demands (industrial demand at bus 3, airport demand at bus 9, and residential demand at bus 12).

The capacity and the operation costs of DVPP units in Southern-Europe Network are depicted in Table 4-1.

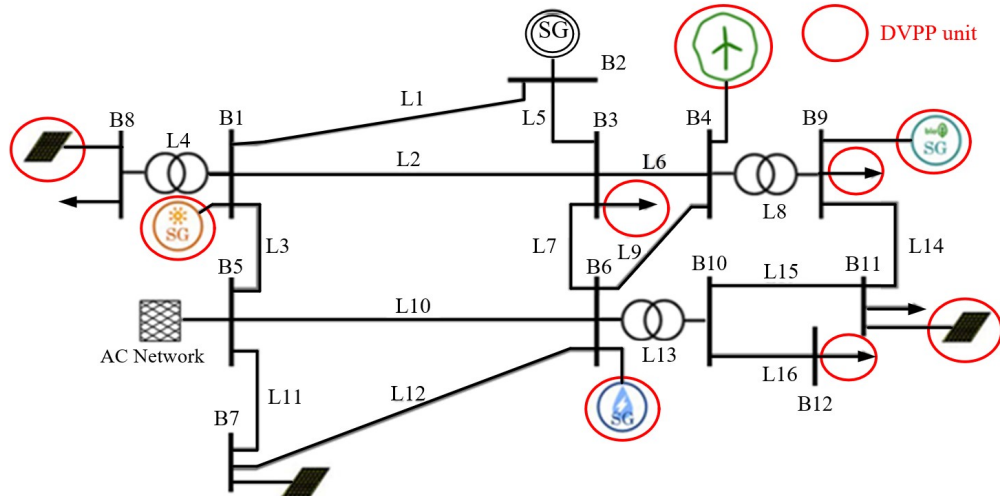


Figure 4-1 Scheme of the Southern-Europe (Spanish) 12-node network and DVPP units

Table 4-1 DVPP units capacity and operation cost in Southern-Europe Network

DVPP Unit	Capacity [MW]	Operation cost [€/MWh]
Hydro plant	40	7.5
Wind farm	50	10
Solar PV1	50	5
Solar PV2	50	5
STU	50	15
Biomass plant	10	23

The main economic and technical data of a 0.5 MW/1 MWh block of Lithium-Ion BES is provided in Table 4-2 and adopted from [4]. As an approximation for the studies carried out in the remainder of this chapter, and for the sake of the comparisons discussed, bigger BESs will be considered by means of appropriately scaling the numbers shown in Table 4-2.

Table 4-2 Lithium-Ion BES data

Total cost [€]	Energy capacity [MWh]	ch./disch. capacity [MW]	Slope of expec. life [-]	ch./disch. efficiency [%]	Self-disch. rate [%]
300000	1	0.5	0.001	95	1

Northern-Europe Network

In Deliverable D1.1, it is proposed to replace some of the solar PV plants and/or STU with additional wind farms and hydroelectric power plants, maintaining the same sub-network topology, to represent the situation of Nordic countries. In this regard, the same network topology as for the Southern-Europe case discussed above, but with different units in the DVPP portfolio, is considered to represent a DVPP in the Nordic countries (see Fig. 4-2). The DVPP in this network consists of one D-RES (hydro plant at bus 6) and three ND-RESs (two wind farms at buses 4 and 8, and a solar PV at bus 11).

The capacity and the operation costs of DVPP units in Northern-Europe Network are depicted in Table 4-3.

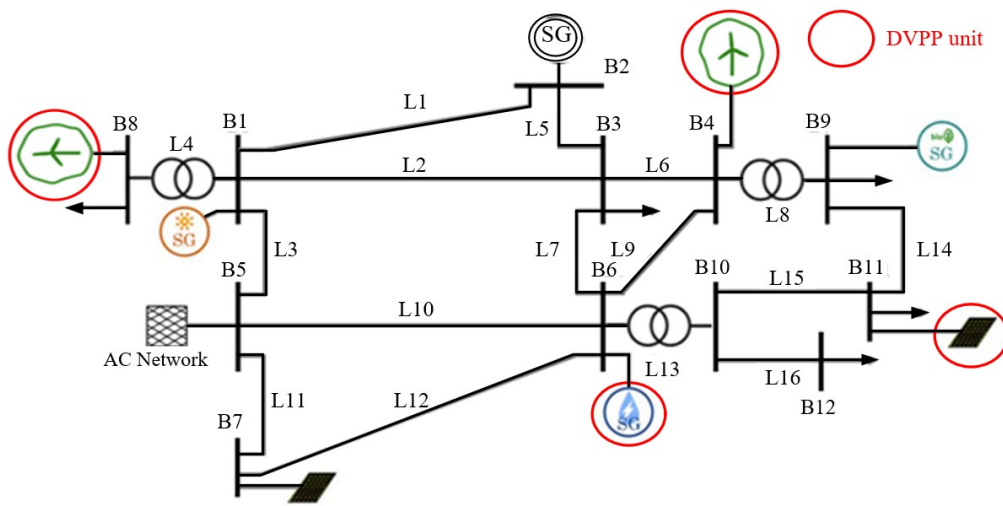


Figure 4-2 Modified scheme of the Northern-Europe (Denmark) 12-node network and DVPP units

Table 4-3 DVPP units capacity and operation cost in Northern-Europe Network

DVPP Unit	Capacity [MW]	Operation cost [€/MWh]
Hydro plant	40	7.5
Wind farm1	150	10
Wind farm2	100	10
Solar PV	50	5

4.1.2 Price, Renewable Source and Demand Profiles

In this section, the forecast data of different uncertain parameters associated with DVPP for different weather conditions and for different electricity markets are presented. The uncertain data includes energy production of ND-RESs, thermal production of STU solar field, demand consumption, and energy and reserve electricity prices.

The robust optimization implemented in the optimal DVPP market bidding tool developed in this Work Package considers the worst-case realization of the uncertainties according to a pre-defined uncertainty robustness budget. This budget is a parameter defined by the user according to the market participation strategy that seeks to be followed according to the robustness strategy (see Deliverable D5.2 for more details on this model). To this aim, only negative deviations of SRM reserve price, renewable source profiles and thermal production of STU solar field are evaluated to define worst-case scenarios, as positive deviations will always benefit the DVPP. Similarly, positive deviations of demand are considered as worst-case scenarios, as negative deviations usually benefit the DVPP. For DAM electricity price forecast, both positive and negative deviations are considered as the worst case can occur in both direction depending on whether the DVPP is a net energy seller or buyer in a given period. The updates of such uncertain profiles for subsequent market sessions (Intra-Day Markets (IDMs)) are considered similarly.

Three cases, optimistic, balanced, and pessimistic, for assigning the robustness strategy of model against uncertainties are considered. In the optimistic case, it is assumed that the forecast data are accurate and are equal to the median value of uncertain parameters. In the balanced case, the uncertain parameters can only deviate in a few hours (between 0 and 3 depending on the market session) from their median values. These hours are the hours that result in worst case of each uncertain parameters. In the pessimistic case, the uncertain parameters can deviate between 1 and 8 hours of the market window. As the last IDMs sessions take shorter time compared to the initial ones, their uncertainty budgets are defined with lower values, i.e., they are considered more accurate. Table 4-4 provides the price and energy uncertainty budgets for the aforementioned cases with respect to the total number of periods for each market window (between brackets).

Selecting the value of the uncertainty budget for each uncertain parameter has a significant impact on the obtained results, and needs to be made based on experience and knowledge of the forecast methods used to generate the different profiles. A thorough analysis of DVPP profit for different uncertain parameters in different electricity markets is presented D5.2, whereas a methodology to decide the *appropriate* robustness strategy is out of the scope of this project.

Table 4-4 Price and energy uncertainty budgets in different electricity markets for optimistic, balanced, and pessimistic cases

Robustness strategy	DAM,SRM, IDM1,IDM2 (24)	IDM3 (20)	IDM4 (17)	IDM5 (13)	IDM6 (9)	IDM7 (3)
Optimistic	0	0	0	0	0	0
Balanced	3	3	2	2	1	0
Pessimistic	8	7	6	4	3	1

Southern-Europe Profiles

The forecast data of the solar irradiation, and thus, of the available solar power production of the PV plants and the STU, in the different markets and for different sample days of spring season in Spain (representing sunny and cloudy days), are adopted from POSYTYF partner CIEMAT (see [5] for more details on the tool used to generate these forecasts). An example of the available power production for sunny and cloudy days for the solar PV plant at bus 8 (PV1) is shown in Fig. 4-3. The DAM available power for other solar powered units is collected in Appendix 5. For the sake of clarity, the forecasts for subsequent markets (i.e., all IDMs) are generated similarly, but not shown in this document.

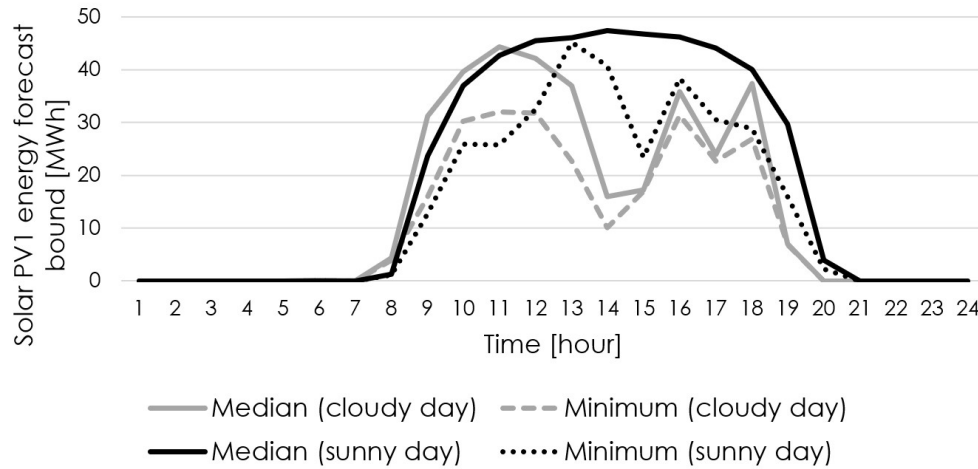


Figure 4-3 Solar PV1 energy forecast bounds

The forecast data of wind farm production for a sample day of spring season in Spain is depicted in Fig. 4-4 and is adopted from POSYTYF partner Iberdrola [6].

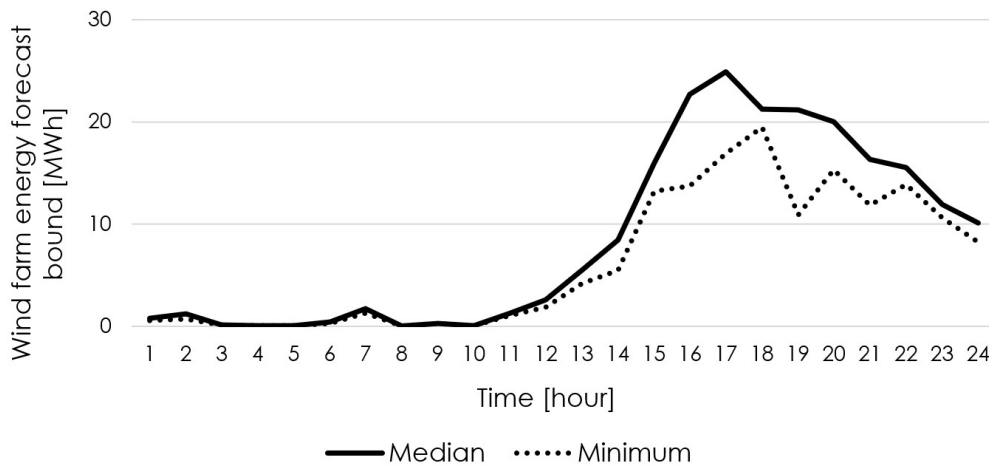


Figure 4-4 Wind farm energy forecast bounds

For the flexible demands, the two-level flexibility model proposed in Deliverable D5.1 is considered. To this aim, three different demand profiles are available for selection in the DAM for each load. Each profile is subject to uncertainties, as shown in Fig. 4-5 for the residential load. Demand profiles of other load types are shown in Appendix 5. After

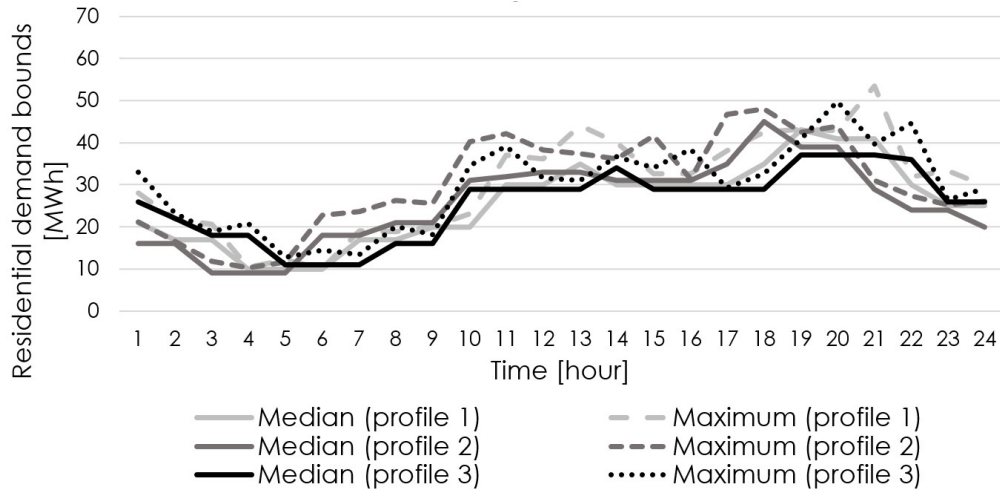


Figure 4-5 Residential demand energy forecast bounds

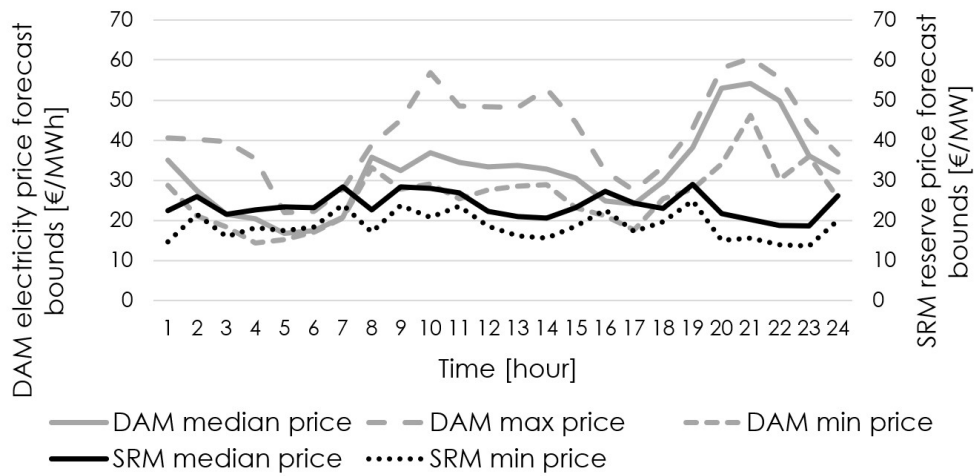


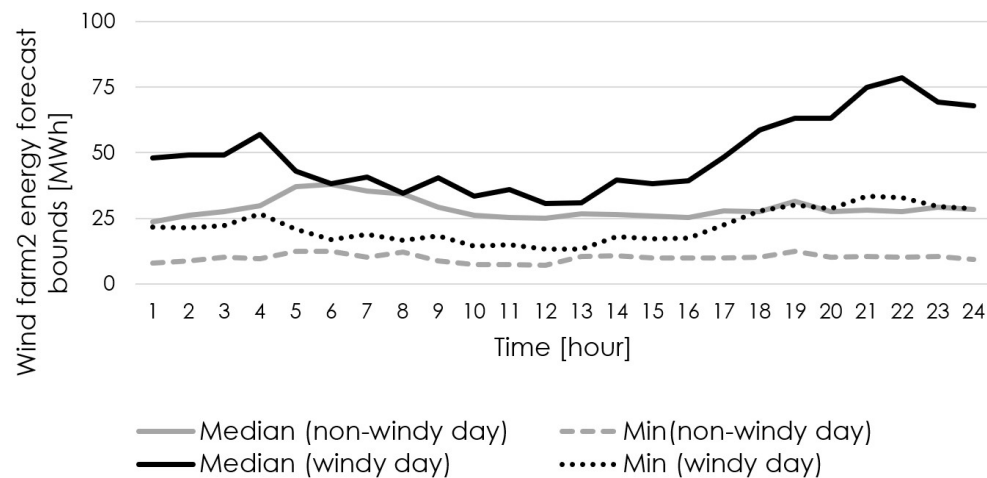
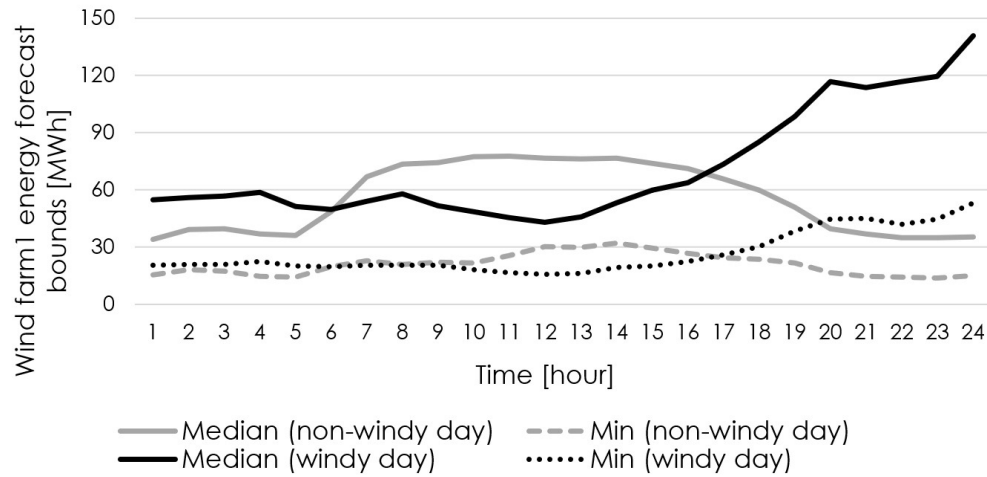
Figure 4-6 DAM electricity price and SRM reserve price forecast bounds

the demand profile is selected in the DAM, the demand owner allows a 10% tolerance for demand flexibility over the selected profile in subsequent markets. More details on this demand flexibility model is provided in [7].

Finally, the DAM electricity price forecast and SRM reserve price forecast bounds for a sample day in Spanish network are represented in Fig. 4-6. The forecast bounds of the seven IDMs for the same day are shown in Appendix 5. All price data are adopted from [8].

Northern-Europe Profiles

The forecast data of the two wind farms available production for different sample days (windy and non-windy) in West Denmark are depicted in Fig. 4-7 and Fig. 4-8, and have been adopted from [9]. The DAM available power for solar PV is similar to solar PV2 in the Southern-Europe Network and is collected in Appendix 5.



The DAM electricity price forecast bounds and SRM reserve price forecast bounds for a sample day in West Denmark are represented in Fig. 4-9 and Fig. 4-10, respectively. All the price forecast data is adopted from [9] for a sample day in West Denmark region.

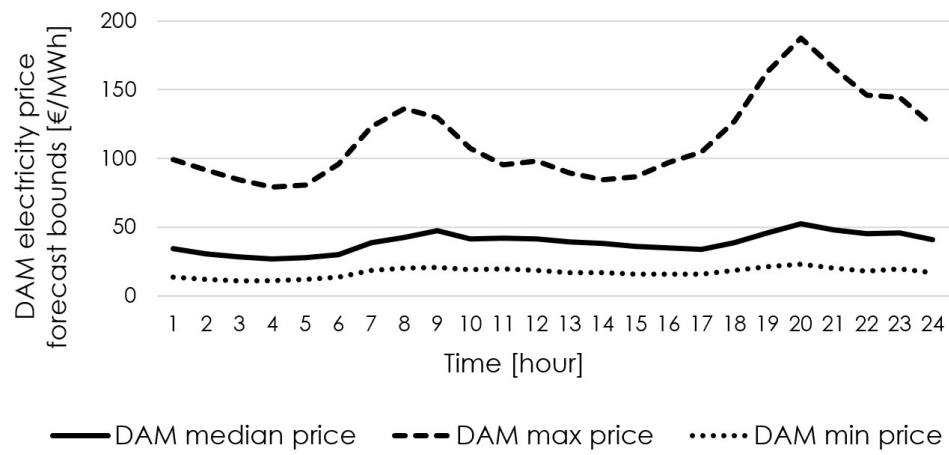


Figure 4-9 DAM electricity price forecast bounds

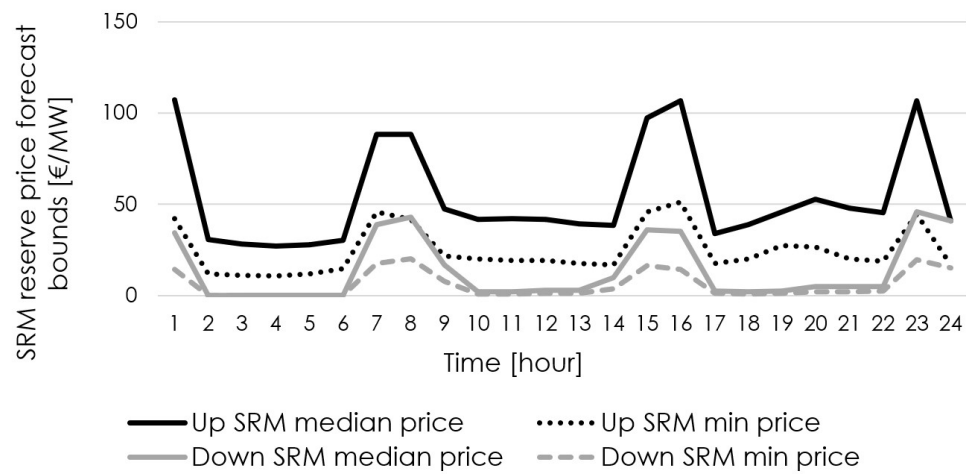


Figure 4-10 SRM reserve price forecast bounds

4.2 Overview of Case Studies and Scenarios

In this chapter, five main case studies are defined to analyze the DVPP economic viability for different conditions, as follows.

- Case 1: To study the performance of different DVPP configurations, for all considered electricity market markets, and for different robustness strategies for the Southern-Europe network in favourable weather (sunny) conditions. <https://www.overleaf.com/project/646eefc16fdecb09f7cc623d>
- Case 2: Similar to Case 1 above, but under adverse weather (cloudy) conditions. Only balanced robustness strategy is considered for comparison.
- Case 3: To compare the viability of DVPPs against electrochemical storage-based alternative solutions for different robustness strategies and weather conditions in the Southern-Europe network.
- Case 4: Similar to Case 1 above, but considering a Northern-Europe scenario.
- Case 5: Similar to Case 2 above, but considering a Northern-Europe scenario.

For each case study, different scenarios are defined, as shown in Tables 4-5, 4-6, and 4-7 according to different characteristics and conditions that can occur for DVPP. The first condition is the market participation strategy followed by the DVPP operator and defined by means of the robustness strategy against different uncertain parameters (robust uncertainty budget), which are defined according to Table 4-4 for different electricity markets. The second condition considers the *rules* that the System Operator may define to be followed by market participants in terms of aggregation as a offering unit (see Deliverable 1.3 for more details), namely (i) No coordination (*No coord.*), where no aggregation of units is allowed for participation in electricity markets; (ii) only ND-RESs are aggregated, to emulate systems where generating units of similar technology or up to certain individual capacity are allowed for aggregation; (iii) any generating unit (ND-RESs + D-RESs) can be aggregated; (iv) any flexible unit, either generating or demand (Gen. + demand) can be aggregated; and the electrochemical storage-based alternative solution (*No coord.* + BES).

The third condition regards the different electricity markets, which include energy (DAM and IDM) and reserve (SRM) markets. The fourth condition is the weather condition defined for each region, according to their predominant stochastic renewable source. Finally, the scenarios are defined based on the location of DVPP in the Southern-Europe (Spain) Network or Northern-Europe (Denmark) Network.

Table 4-5 Description of scenarios of Case Study 1 and 2

Characteristic		Scenario							
		1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4
Strategy	Optimistic	✓	✓	✓	✓	-	-	-	-
	Balanced	✓	✓	✓	✓	✓	✓	✓	✓
	Pessimistic	✓	✓	✓	✓	-	-	-	-
DVPP portfolio	No coord.	✓	-	-	-	✓	-	-	-
	Only ND-RESs	-	✓	-	-	-	✓	-	-
	ND-RESs + D-RESs	-	-	✓	-	-	-	✓	-
	Gen. + demand	-	-	-	✓	-	-	-	✓
	No coord. + BES	-	-	-	-	-	-	-	-
Market window	DAM	✓	✓	✓	✓	✓	✓	✓	✓
	SRM	✓	✓	✓	✓	✓	✓	✓	✓
	IDMs	✓	✓	✓	✓	✓	✓	✓	✓
Weather	Sunny	✓	✓	✓	✓	-	-	-	-
	Cloudy	-	-	-	-	✓	✓	✓	✓
Network	Spain	✓	✓	✓	✓	✓	✓	✓	✓
	Denmark	-	-	-	-	-	-	-	-

Table 4-6 Description of scenarios of Case Study 3

Characteristic		Scenario			
		3.1	3.2	3.3	3.4
Strategy	Optimistic	✓	-	-	-
	Balanced	-	✓	-	✓
	Pessimistic	-	-	✓	-
DVPP portfolio	No coord.	✓	✓	✓	✓
	Only ND-RESs	✓	✓	✓	✓
	ND-RESs+D-RESs	-	-	-	-
	Gen. + demand	-	-	-	-
	No coord. + BES	✓	✓	✓	✓
Market window	DAM	✓	✓	✓	✓
	SRM	✓	✓	✓	✓
	IDMs	-	-	-	-
Weather	Sunny	✓	✓	✓	-
	Cloudy	-	-	-	✓
Network	Spain	✓	✓	✓	✓
	Denmark	-	-	-	-

Table 4-7 Description of scenarios of Case Study 4 and 5

Characteristic		Scenario					
		4.1	4.2	4.3	5.1	5.2	5.3
Strategy	Optimistic	✓	✓	✓	-	-	-
	Balanced	✓	✓	✓	✓	✓	✓
	Pessimistic	✓	✓	✓	-	-	-
DVPP portfolio	No coord.	✓	-	-	✓	-	-
	Only ND-RESs	-	✓	-	-	✓	-
	ND-RESs+D-RESs	-	-	✓	-	-	✓
Market window	DAM	✓	✓	✓	✓	✓	✓
	SRM	✓	✓	✓	✓	✓	✓
	IDMs	-	-	-	-	-	-
Weather	Windy	✓	✓	✓	-	-	-
	Non-windy	-	-	-	✓	✓	✓
Network	Spain	-	-	-	-	-	-
	Denmark	✓	✓	✓	✓	✓	✓

4.3 Simulation Results

This Section starts with a complete techno-economic analysis regarding DVPP participation in different electricity markets for different weather conditions in the Southern-Europe Network, which is presented in Subsection 4.3.1. This analysis serves to illustrate, in a comprehensive manner, all information and details that are involved in each of the units that comprise the DVPP when carrying out each of the different scenarios of each case study defined above. In particular, Scenarios 1.4 (Section 4.3.1) and 2.4 (Section 4.3.1) are presented for the DAM. The analysis is then continued in Section 4.3.1 with a study of the the total traded energy, profits and costs of the DVPP in different energy and reserve markets for a sunny day and balanced robust strategy. Sections 4.3.2-4.3.5 then provide a more synthesized comparison of the 5 case studies and their different scenarios, with special focus on the economic results.

4.3.1 Detailed Analysis of DVPP Participation in Electricity Markets under Uncertainty – A Southern-Europe Case

In this Section, results from Scenarios 1.4 and 2.4 are analyzed for the DAM to get a better understanding of the DVPP performance. The DVPP portfolio comprises all units that were defined in Section 4.1.1 for the Southern-Europe (Spanish) case, namely two solar PV and one wind plants, an STU, a hydroelectric and a biomass power plants, and three flexible demands.

DVPP participation in the DAM for sunny day - Scenario 1.4

Figure 4-11 shows the DAM electricity price forecast bounds and DAM traded energy in the sunny day for optimistic, balanced, and pessimistic cases. The optimistic case represents when the forecast data for all uncertain parameters (including ND-RESs production, STU solar field thermal production, demand, and DAM electricity price) are equal to their median forecast value. In the balanced case, the DVPP operator considers 3 hours in the whole period for possible deviation of each uncertain parameter to its worst case. In the pessimistic case, the possible deviation of uncertain parameters in 8 hours out of the 24 h period is considered. The different uncertainty budgets defined for price and energy according to the market participation strategy are defined in Table 4-4.

For the optimistic case, in most of the hours (1-6, 10-24) the DVPP is selling energy in the DAM by considering an accurate forecast data for uncertain parameters. The DVPP sold energy between hours 11-19 is much higher than other hours due to high production of ND-RESs. Although the median electricity price is higher in the last hours of day (20-22) compared to other hours, the DVPP sold energy in the market is significantly decreased due to zero production of solar PV units and the decrease of STU production and also the increase of DVPP residential demand. The DVPP only buys energy in hours 7-9 to supply its demands as in these early morning hours demands start to increase and the ND-RESs do not have a significant production yet.

For the balanced case, the energy that is sold by the DVPP is substantially decreased between hours 11-19 compared to the optimistic case. This is due to deviation of ND-RESs

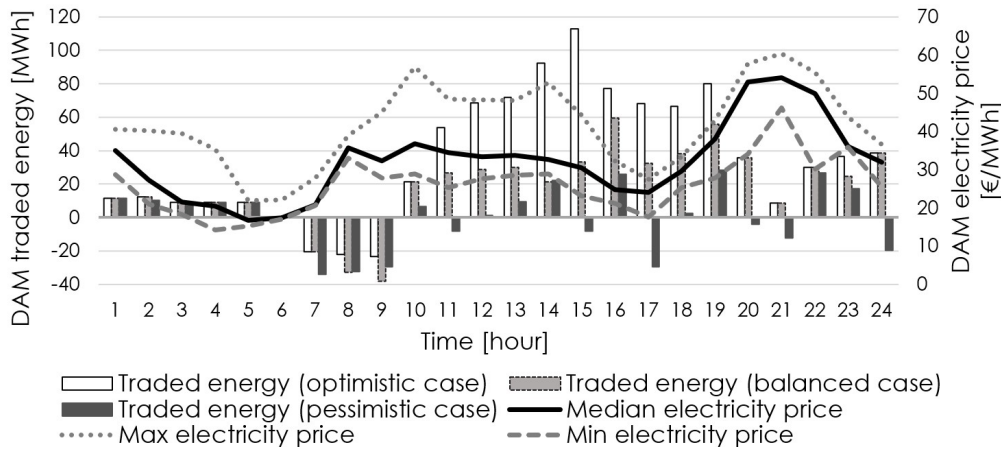


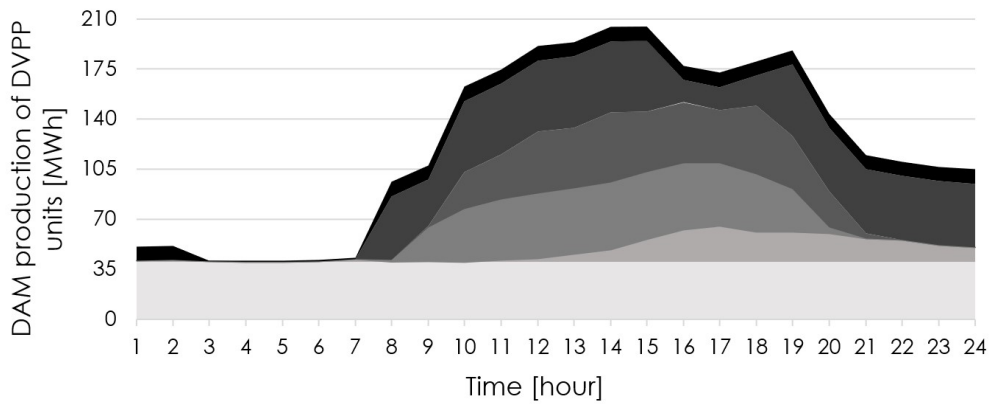
Figure 4-11 DAM electricity price forecast bounds and DAM traded energy in the sunny day for optimistic, balanced, and pessimistic cases

and STU energy production to lower values, the deviation of demand to higher values, and the DAM price deviation to lower values for these hours that the DVPP is selling energy. As the ND-REs and STU do not have any production (or very low production) in the first hours (1-6) and the demands are low, the DVPP sold energy in these hours is similar to the optimistic case. In the hours 8-9, the DVPP operator buys a little bit more energy in the DAM. Although the DVPP operator can select a different profile for each demand, and consequently the total demand is lower in this case compared to optimistic case, the lack of production due to considering uncertainty justifies this issue.

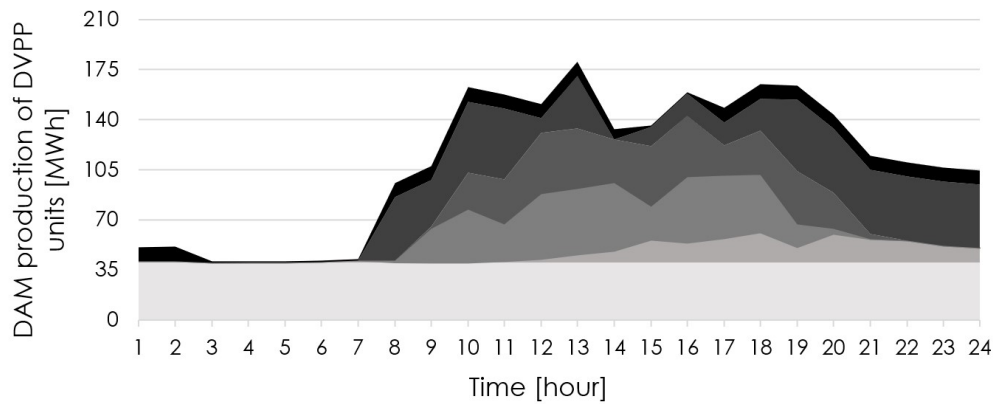
For the pessimistic case, the DVPP sells less energy in the DAM compared to optimistic and balanced cases and even in some hours (11, 15, 17, 20, 21, 24) that the DVPP was energy seller in the optimistic case and balanced case, it becomes energy buyer. This fact shows the importance of selecting an appropriate robustness strategy for the DVPP operator, which can even change the direction of trading energy (buying or selling). The reason behind buying a substantial amount of energy in hour 17 is that the prediction bounds for most of the uncertain parameters in this hour have high variation and this hour is selected as the worst case. Another interesting remark from Fig. 4-11 can be obtained by comparing the amount of energy that is bought by DVPP between hours 8-9 for pessimistic case compared to balanced case. In particular, the DVPP operator buys more energy between these hours in the balanced case than to pessimistic case. The reason is that more hours for demand variation are considered in the pessimistic case and as a result a different profile type for each demand is selected that has lower value in these hours. This shows the relevance of having flexible demands in the DVPP portfolio.

Figure 4-12 shows the DAM production of DVPP units in the sunny day for optimistic, balanced, and pessimistic strategies, whereas Fig. 4-13 compares the total DAM production of DVPP for the above cases.

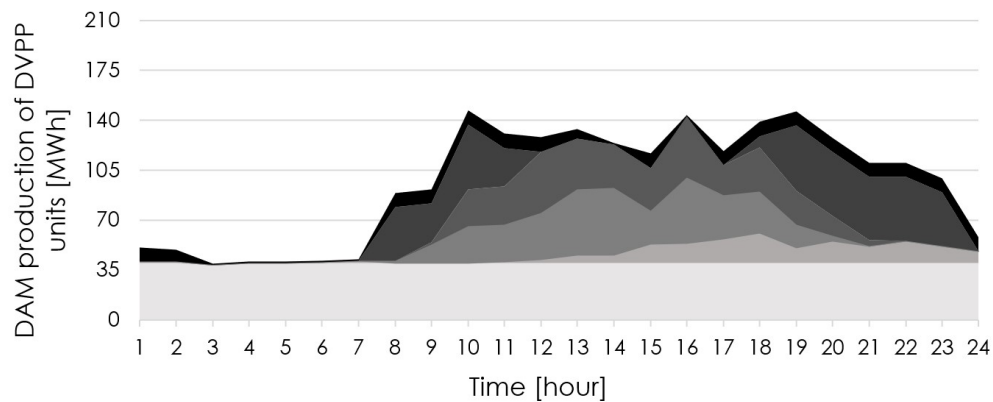
For the optimistic case, the DVPP produces less than 55 MWh between hours 1-7 that mainly is produced by the hydro plant. The biomass plant production is reduced after hour 2 until hour 7 as the residential demand is decreased between hours 3-5 comparing to early hours 1-2. Besides the production cost of biomass plant is much higher than hydro plant thus the DVPP uses it when the demand or/and the electricity price is high. Therefore except hours 3-7, the biomass plant produces its maximum energy so that DVPP can use its



a) Optimistic strategy



b) Balanced strategy



c) Pessimistic strategy

Figure 4-12 DAM production of DVPP generating units for different market participation strategies for a sunny day in the Spanish system

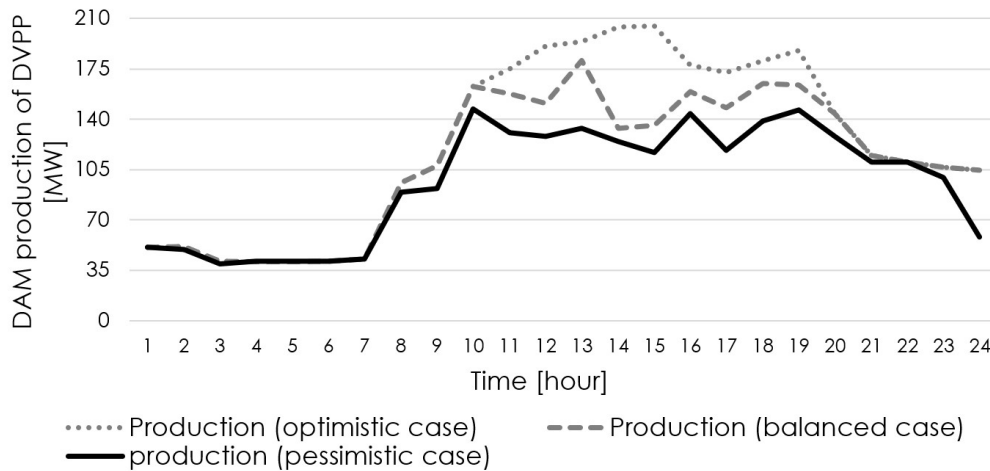


Figure 4-13 DAM production of DVPP in the sunny day for optimistic, balanced, and pessimistic cases

production to supply its demands or to arbitrage energy. The STU starts producing energy at hour 8 and produces energy until hour 24. The STU makes use of its thermal storage for production in this early hour helps to alleviate the early peak demand. The solar PV2 starts producing about 1 hour later than solar PV1 as it is located in different geographical location with later sunrise time. The DVPP has high hourly production (more than 100 MWh) between hours 9-24 due to high penetration of both D-RESs and ND-RESs. Therefore, in most of these hours (except hour 9 that demand is high), the DVPP is a net energy seller in the electricity market. The hourly production of DVPP units reaches about 200 MWh between hours 14-15 which results in trading even more energy in the DAM.

For the balanced case, the production of ND-RESs and STU is decreased in three hours of the day that has highest impact on production of these units. The STU produces much lower than its capacity in hours 12 and 14-18 and even in hour 14, it does not have any production. This is due to the fact that it uses most of the available energy from the solar field to charge its storage during these hours to arbitrage energy after hour 18, when energy has high price and also to supply the second peak of demand. The uncertainty of price in the balanced case results in less production of biomass plant at hour 14, and its minimum production between hours 15-16, due to their high operation cost.

For the pessimistic case, the production of DVPP is decreased compared to balanced case due to the lower availability of stochastic energy sources. Therefore the hourly production of DVPP units is less than 150 MW in all time periods. The volatility of price is also much higher than balanced case, therefore the biomass plant has low production in hours 13, 14, and 16. Besides, the STU production between hours 12-18 is either zero or very small.

According to Fig. 4-13, the production of DVPP in the balanced and pessimistic cases compared to optimistic case is mainly decreased between hours 10-20, i.e., when the DVPP has high penetration of ND-RES production. The total production of DVPP in the whole time periods for balanced and pessimistic cases is reduced by 10% and 21% compared to optimistic case, respectively. Besides, the volatility of the hourly production is increased by adopting more severe robustness strategies.

Figure 4-14 shows the DAM consumption of DVPP flexible demand units in the sunny day for optimistic, balanced, and pessimistic cases. The two-level flexibility model developed for these flexible demands allows choosing the optimal profile for each of the three loads according to the different uncertainty conditions in order to maximize the overall DVPP benefit (see Appendix 5 Figs. A-5 – A-7). Figure 4-15 compares the total demand of DVPP for the above cases.

For the optimistic case, profiles 2 and 3 are selected for the industrial and airport demands, respectively, whereas profile 1 is selected for the residential demand. The DVPP operator prefers to supply the peak of industrial demand in early hours 8-14 instead of late hours 15-21, as DVPP has high production in these hours and the electricity price is lower than late hours. The late profile 3 is selected for airport demand as in hours 9-10 (hours with highest demand in profile 3) due to sunrise, the total production of Solar PVs and STU is higher than hours 8-9 (hours with highest demand in profiles 1 and 2 of the airport demand). Although having high demand in hours 8-9 is not appropriate for DVPP, the early profile 2 is selected for industrial demand. Actually the time span for peak hours of the industrial demand is an important criteria to select profile 2. The average electricity price between hours 8-14 is lower compared to hours 15-21. As a result, the DVPP operator can compensate the negative profit in hours 8-9 by having lower demand in hours 15-21. The DVPP operator prefers to select the early profile 2 of residential demand as it avoids the high demand in late hours in basecase profile 1 and late profile 3 (which in turn implies higher price of electricity in late hours).

For the balanced case, considering volatility of demand due to uncertainty affects selecting the best profile of residential demand. As both demand and electricity price can have higher values than their median values in this case, the DVPP operator decides to select the early profile 2 for residential demand to avoid high cost. Besides, the DVPP operator selects appropriate profiles of demands by considering the lower production of ND-RESs and STU. Similar to optimistic case, profile 2 is selected for residential demand and profile 3 is selected for airport demand.

For the pessimistic case, profile 1 is selected for industrial load to avoid high demand between hours 8-14, which was the case in the optimistic and balanced cases. The selected profiles for airport and residential demands are the same as for the balanced case. The overall consumption is higher for the three loads compared to previous cases as more volatility is considered for uncertain parameters. This leads DVPP to buy more electricity from the DAM to supply its demands compared to previous cases.

According to Fig. 4-15, it is understandable that by adopting a more conservative strategy, generally the total demand increases. For instance, the total demand of the DVPP in the pessimistic case between hours 15-24 is higher than optimistic and balanced cases. Moreover, the total demand of DVPP in the whole time periods for balanced and pessimistic cases is increased by 5% and 10% compared to optimistic case, respectively. However, there are some hours (like hours 8-10 and 13-14) that the DVPP demand in the pessimistic case is lower than optimistic and/or balanced cases due to possibility of selecting different demand profiles. Therefore, the flexibility of demands help the DVPP operator to reduce the increase of demand costs when more conservative strategies are considered.

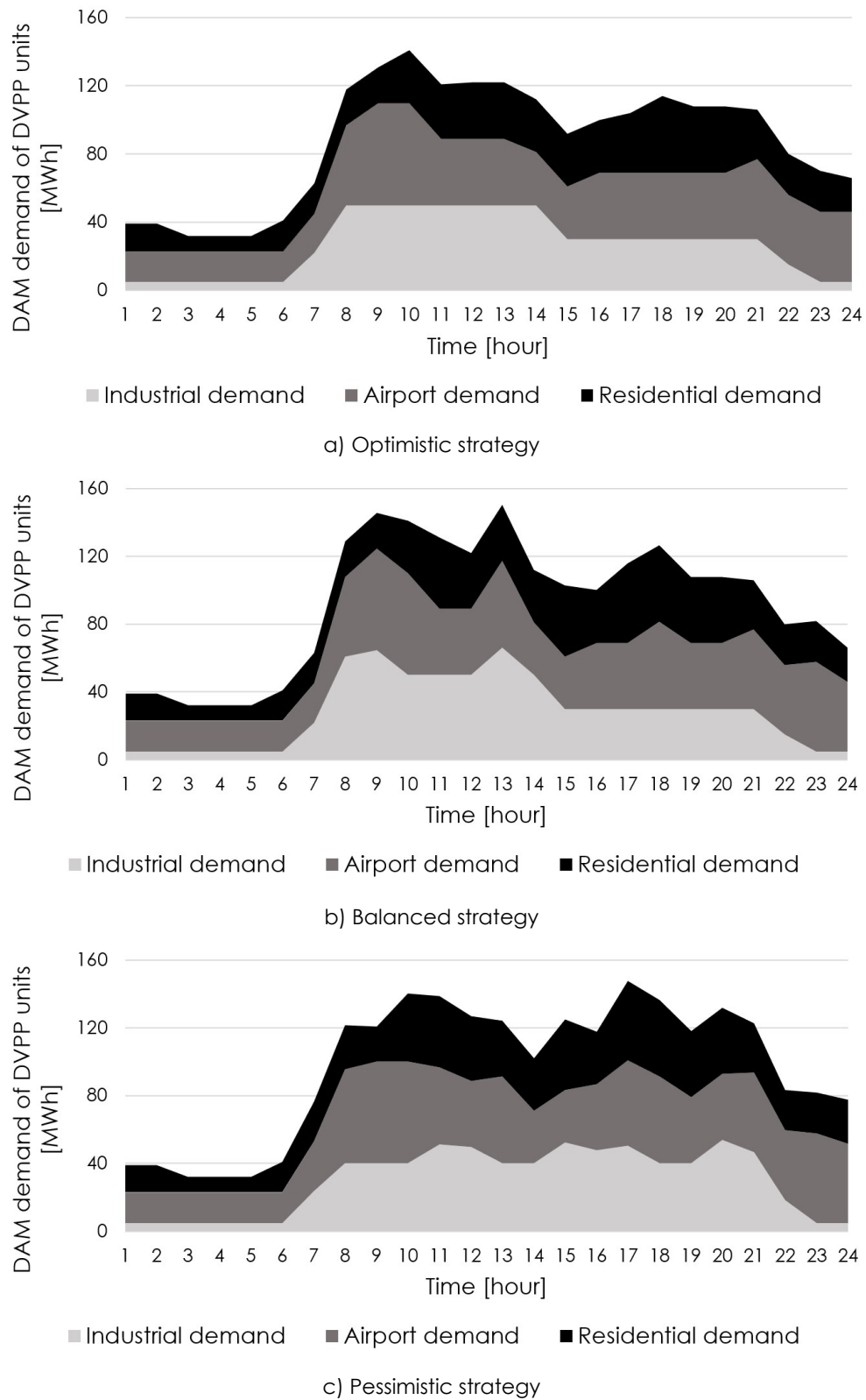


Figure 4-14 DAM consumption of DVPP flexible demand units for different market participation strategies for a sunny day in the Spanish system

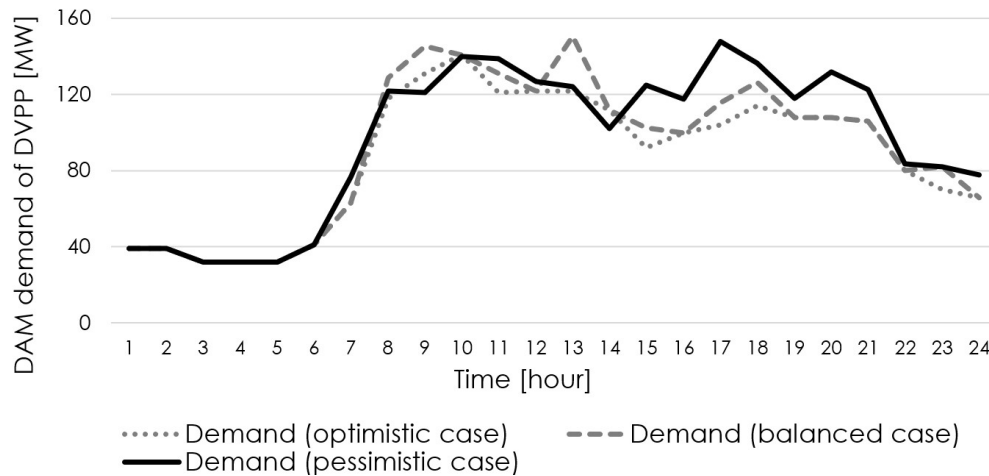


Figure 4-15 DAM demand of DVPP in the sunny day for different market participation strategies

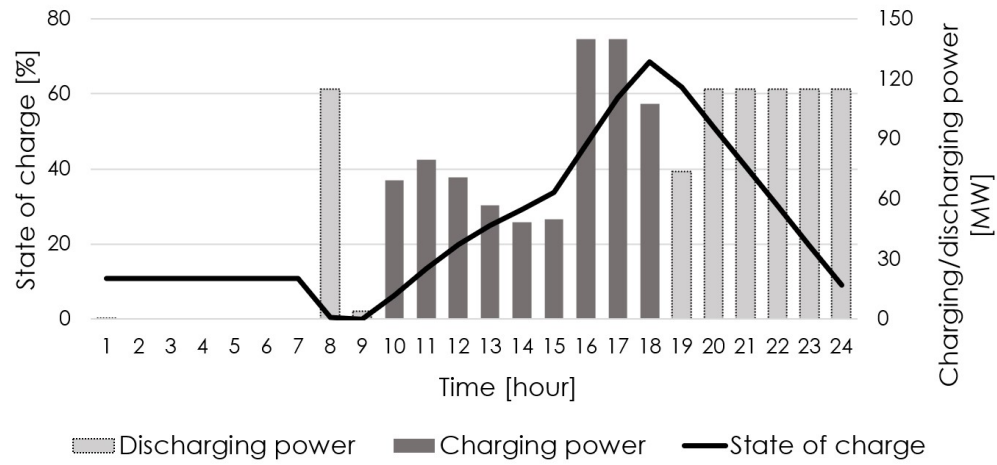
Another relevant quantity to analyze in these studies is the State of Charge (SoC) of the STU, i.e., the percentage of energy available in the STU molten-salt thermal storage with respect to its total capacity. In this regard, Fig. 4-16 represents the DAM SoC and charging/discharging power of STU thermal storage in the sunny day for optimistic, balanced, and pessimistic cases. A summary of the results shown in Fig. 4-16 is provided in Fig. 4-17.

For the optimistic case, the STU thermal storage discharges between hours 8-9 and 19-24, i.e., when the DVPP demand and DAM electricity price are high. The discharging process of the STU storage significantly helps the STU supply the early peak demand of DVPP at hour 8. The STU thermal storage is in charging state between hours 10-18. This way, the STU can produce energy during night hours 19-24n when solar PV plants have stopped generating power.

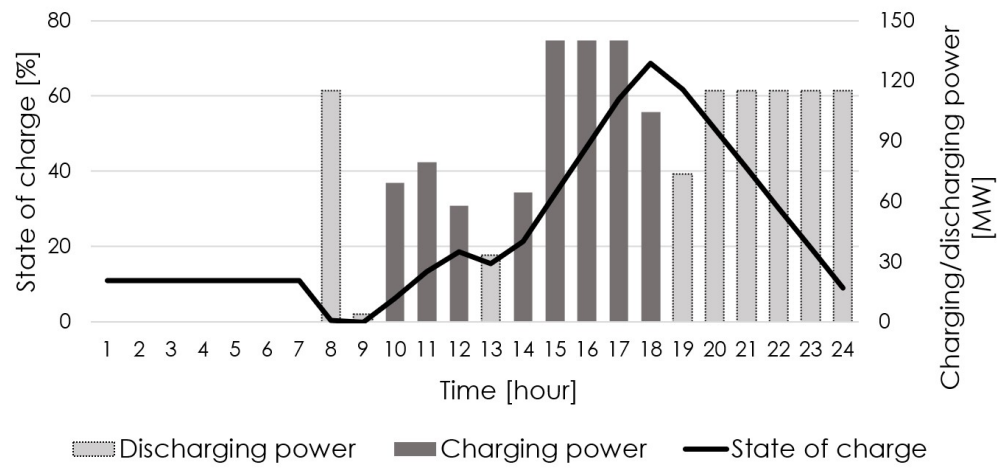
For the balanced case, there are some differences compared to optimistic case in the charging/discharging power and SoC of STU thermal storage. The STU thermal storage discharges at hour 13 to compensate the increase of demand at this hour (see Fig. 4-14). Besides, the charging power of STU thermal storage is increased between hours 14-15 compared to optimistic case to compensate the lower SoC. In this way, the STU thermal storage has same discharging power between hours 19-24 as in the optimistic case.

For the pessimistic case, the STU thermal storage charging/discharging processes are reduced compared to optimistic and balanced cases in most of the hours since more volatility in solar field production is considered. However, the charging power at hour 18 is slightly increased compared to balanced case. This is due to the fact that DVPP demand at hour 17 is high (see Fig. 4-14), and the best hour after hour 17 for storing energy in order to providing energy in late hours 19-23 is hour 18 in which the DVPP demand and electricity price are relatively low.

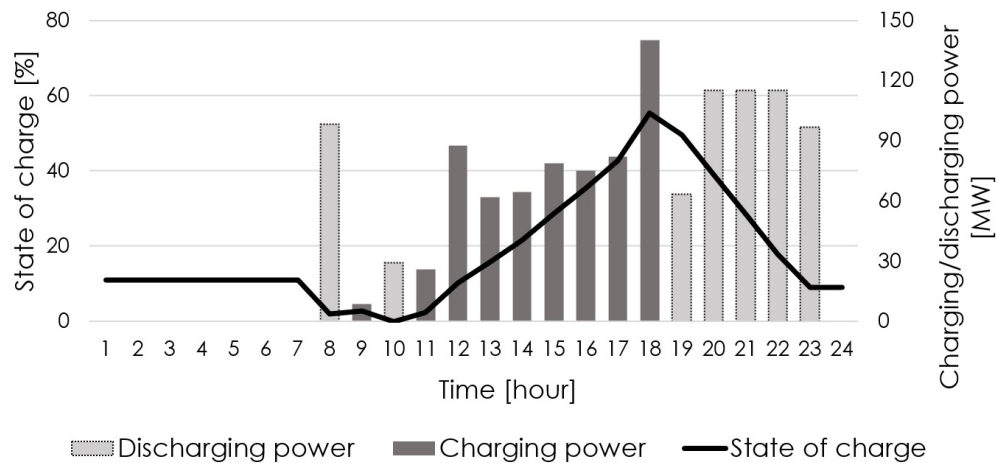
According to Fig. 4-17, the SoC of STU thermal storage for pessimistic case is lower than optimistic and balanced cases in most of the hours. The total SoC of STU thermal storage in the whole periods for balanced and pessimistic cases compared to optimistic case is reduced by 3% and 24.4%, respectively. Although the value of SoC is lower for pessimistic case, a similar trend is observed throughout the day in all three cases. Usually STU thermal storage reaches its maximum SoC at hour 18 and then it starts to discharge power.



a) Optimistic strategy



b) Balanced strategy



c) Pessimistic strategy

Figure 4-16 SoC and charging/discharging power of STU thermal storage for different DAM market participation strategies for a sunny day in the Spanish system

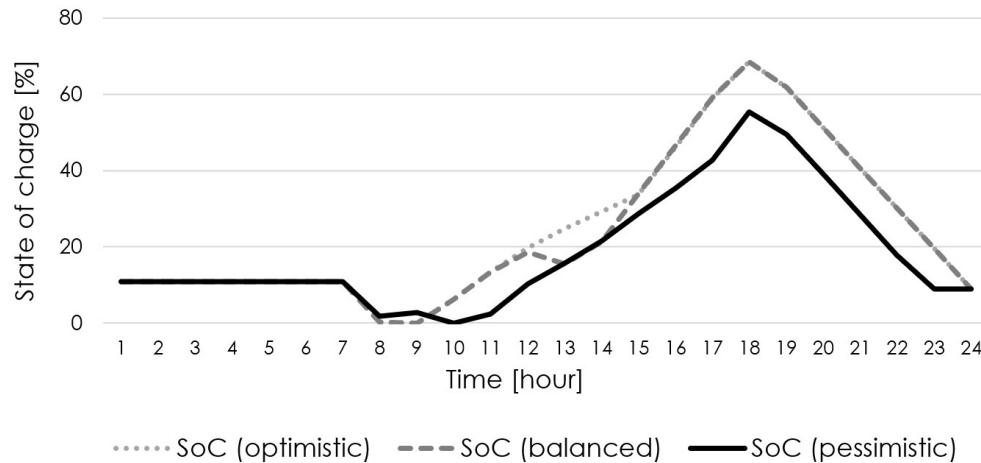


Figure 4-17 DAM SoC of STU thermal storage in the sunny day for optimistic, balanced, and pessimistic cases

DVPP participation in the DAM for cloudy day - Scenario 2.4

In this Section, a similar analysis to that carried out in the section above is presented. This time, considering adverse weather (cloudy) conditions in the Southern-Europe (Spanish) DVPP. Figure 4-18 shows the DAM electricity price forecast bounds and the resulted DAM traded energy for the three different market participation strategies.

For the optimistic case, the DVPP sells electricity in hours 1-5, 10-12, 16-23, buying energy in the remaining periods. By comparing Fig. 4-18 and Fig. 4-11, it can be concluded that the DVPP sells less and buys more electricity in the cloudy day compared with the sunny day. Besides, the DVPP becomes energy buyer in hours 13, 14, and 24, when it behaved as a net energy seller in the sunny day. The reason is that according to Figs. A-1 – A-3, the solar PVs and STU forecast energies in the DAM for the cloudy day after hour 13 are significantly decreased compared to the sunny day. Therefore the DVPP has to compensate this lack of energy by buying electricity from the market to supply its demands.

For the balanced case, the total energy that is sold/bought by DVPP overall is decreased/increased by 52%/75% compared to optimistic case due to considering the fluctuations of uncertain parameters. In addition to hours 7-9, 13, 14, and 24 during which the DVPP buys electricity from the market in the optimistic case, the DVPP buys in more hours 11, 15, 18, and 23 for the balanced case. Besides, the DVPP sold energy in hours 12, 16, 17, and 19 is reduced compared to optimistic case.

For the pessimistic case, the DVPP buys electricity in most of the hours (hours 7-21, and 23-24) as more uncertain hours are considered in this case compared to balanced case. The total energy that is sold/bought by DVPP in whole periods is decreased/increased by 79%/209% compared to optimistic case. As most of the DVPP production in the first 5 hours comes from D-REs, the DVPP traded energy is equal/close to balanced and optimistic cases.

It has been observed thus that applying different market participation strategies, and having adverse weather conditions, will have a significant impact on the economic results of the DVPP, as will be thoroughly discussed in subsequent Sections.

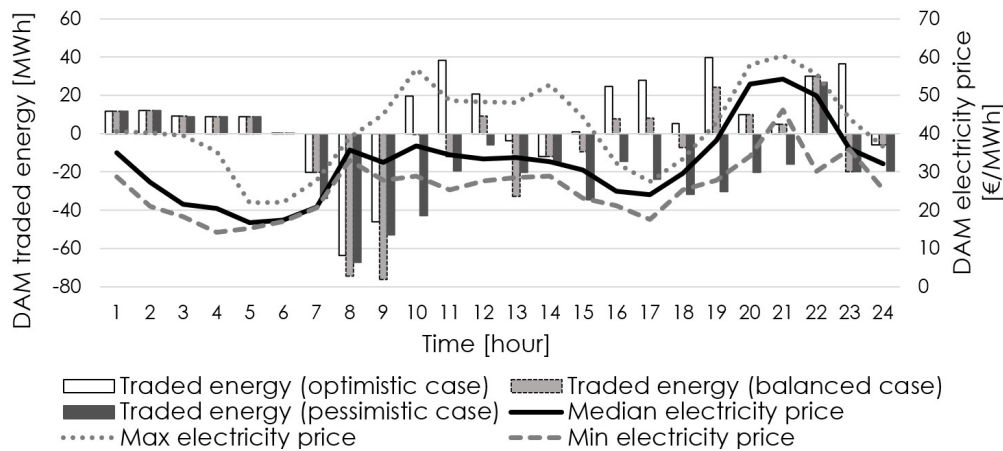


Figure 4-18 DAM electricity price forecast bounds and traded energy in the cloudy day for optimistic, balanced, and pessimistic cases

A comparison of the DAM total production of the DVPP generating units in these conditions for different strategies is provided in Fig. 4-19. To facilitate the reading of this Chapter, and for the sake of completeness, detailed productions of each generating unit, similar to that shown in Fig. 4-12 can be found in Fig. B-1 of Appendix 5.

The total production of DVPP units in the cloudy day is decreased by 23% compared to sunny day. Note that the wind farm, hydro, and biomass plants production are similar to sunny day and they usually are operated in their maximum production capacity. Note that SRM is not yet considered in the scenarios discussed in this Section.

For the balanced case, the DVPP ND-RES units production is decreased due to considering the uncertainties. The total production of DVPP units overall is reduced by 7% compared to optimistic case.

For the pessimistic case, the production of DVPP is significantly reduced to less than 120 MWh for all periods. In this case, the total production of DVPP units overall is reduced by 15% compared to the optimistic case.

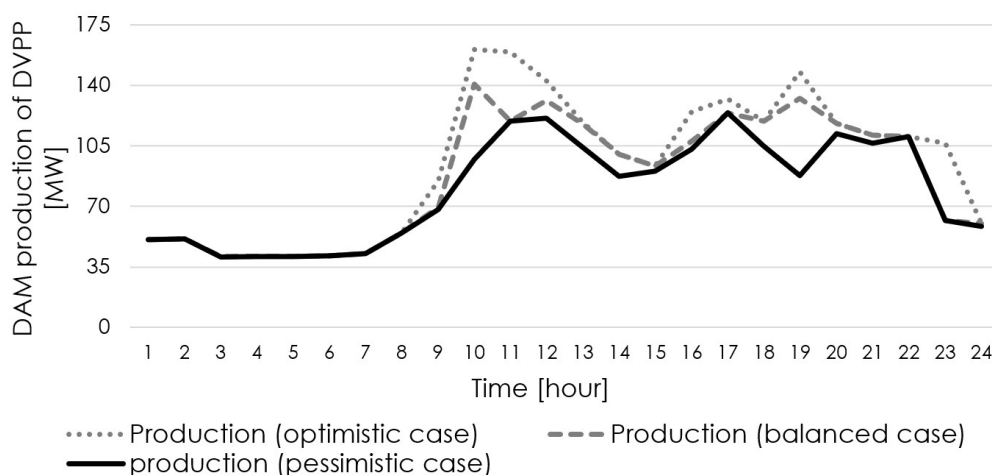


Figure 4-19 DAM production of DVPP in the cloudy day for optimistic, balanced, and pessimistic cases

Finally, the production of DVPP in the balanced and pessimistic cases compared to optimistic case is decreased more significantly between hours 10-13 and 18-20, and 23. These hours are usually the hours that ND-RES production has highest production forecast deviations compared to other hours and have worse effect on results.

Regarding the flexible demand behaviour under adverse weather conditions, since the same data (i.e., profiles available for each demand) is considered for both sunny and cloudy conditions, same results as those shown in Figs. 4-14 and 4-15 have been obtained in this case, and are not repeated here.

Results of the SoC of the STU for the conditions considered in this Section and for the three market participation strategies are compared in Fig. 4-20. Again, to facilitate the reading of this Chapter, and for the sake of completeness, details on the charging/discharging power at each period of the market window, and the corresponding SoC for each strategy, are presented in Fig. B-1 of Appendix 5.

It can be observed from Fig. 4-20 that the SoC of STU thermal storage for pessimistic case is increased with lower slope compared to optimistic and balanced cases. This is due to lower thermal production of solar field and also the discharging state at hour 10 for the optimistic and balanced cases which is not the case for the pessimistic case. The total SoC of STU thermal storage over the whole market window for the balanced and pessimistic cases compared to optimistic case is reduced by 13% and 16%, respectively.

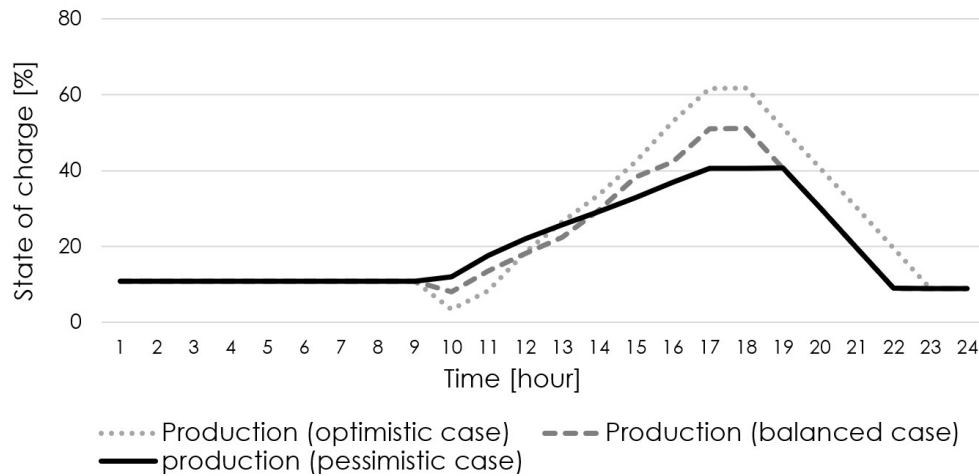


Figure 4-20 DAM SoC of STU thermal storage in the cloudy day for optimistic, balanced, and pessimistic cases

DVPP participation in different electricity markets -Scenario 1.4

Figure 4-21a) shows the DVPP traded energy and available up/down Secondary Reserve (SR) in the DAM+SRM in the sunny day for balanced case. In the DAM+SRM optimization problem both energy and reserve are optimized but only the energy is offered in the electricity market. The up/down SR will be re-optimized in the SRM+IDM1 problem with more accurate forecast data. The detailed bidding strategy of DVPP in the sequential markets is illustrated in Deliverable D5.2. The DVPP in this case is selling electricity in most hours, and only buys electricity between hours 3-9 when demand is high and the ND-RESs production is negligible. The DVPP also can provide both up/down SR in all periods. The

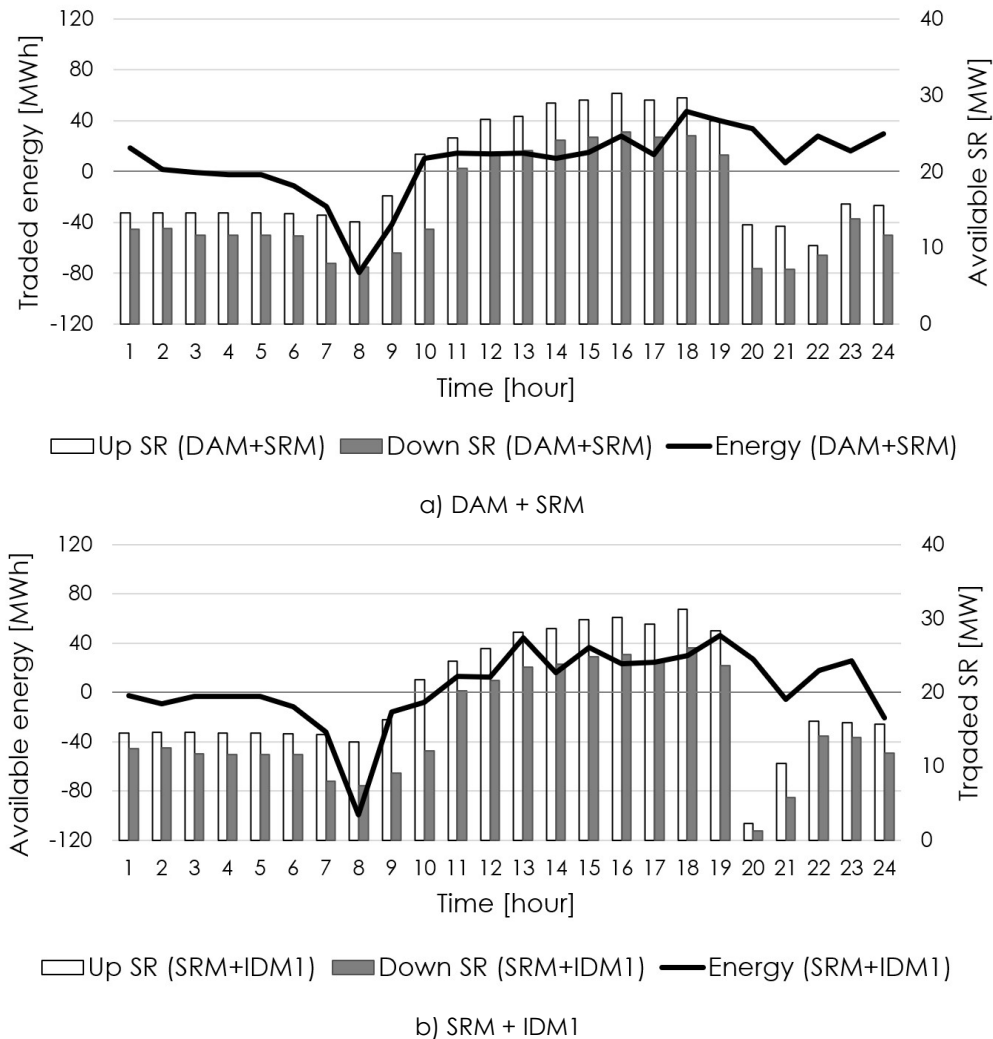


Figure 4-21 DVPP energy and SR in different market windows of the Spanish system (sunny day, balanced case)

amount of provided down reserve is lower than up reserve in all hours since the system operator requests lower amount of down reserve compared to up reserve in the proposed sample day. The DVPP available up/down SR between hours 10-19 is higher than in other hours since the ND-RES units have more available power in these hours.

Figure 4-21b) shows the DVPP available energy and traded up/down SR in the SRM+IDM1 in the sunny day for balanced case. In the SRM+IDM1 problem of the market both IDM1 energy and reserve are optimized but only the up/down SR is offered in the electricity market. The black line in the figure depicts the energy that is traded in the DAM+SRM problem plus the adjusting power that is expected for IDM1. The DVPP prefers to buy electricity in more hours compared to previous market sessions. Therefore, the available energy at hours 1-10, 21, and 24 is negative. Besides, the available energy is increased/decreased compared to previous market sessions so that the DVPP reaches more profit. The traded up/down SR is changed compared to DAM+SRM in hours 9-24 and the effect is more substantial in hours 20 and 22. The main reason behind this change is the update of forecast data which leads to more accurate bidding strategy and more profit for the DVPP.

Figure 4-22 shows the DVPP traded energy in different IDMs in the sunny day for balanced case. The total amount of energy (from the DAM+SRM problem until the associated IDM) is illustrated in these figures to provide a better insight regarding the adjustments in each specific IDM. The total traded energy in the DAM+IDM1 is negative in hours 2, 6-9, and 24, and in other hours the DVPP is a net seller in the energy markets. The amount of energy that DVPP buys in hour 8 is substantially decreased compared to DAM+SRM problem since the forecast data is updated for IDM1. There are some other significant adjustments in other IDMss. For example, the DVPP buys energy in IDM3 at hour 14 so the total traded energy (from the DAM+SRM problem until IDM3) in this hour is reduced.

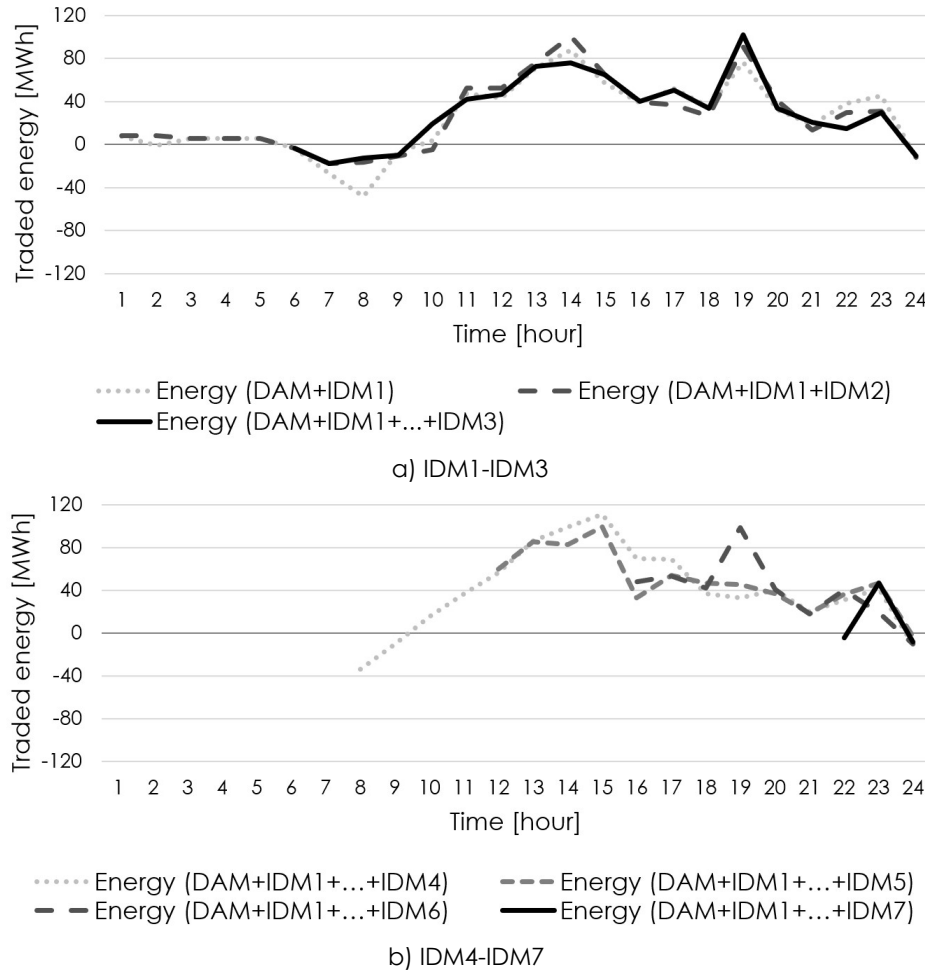


Figure 4-22 DVPP traded energy in different market sessions of the Spanish system (sunny day, balanced strategy)

Table 4-8 provides the DVPP profit and costs in different electricity markets in the sunny day for balanced case. The profit and different costs in this table represent the data that are related to traded energy or reserve. The column *Profit* collects the objective function value resulting from solving the optimization problem. The column *Incomes* represent the expected incomes/expenses from selling/buying energy in the market based on the median of the price forecast, i.e., it corresponds to the result of the optimistic case, and can be either positive or negative (see the first row of eq. (2.1)). The column *Operation cost* are the sum over the time horizon of the hourly variable and operation costs of the D-REs, and the operation and maintenance costs of the ND-REs of the DVPP (see the

Table 4-8 DVPP profit and costs in different electricity markets in the sunny day for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	-15420	7196	21996	620
SRM	20275	19846	-1348	918
IDM1	10035	14087	3454	598
IDM2	1299	2244	737	208
IDM3	205	98	-176	69
IDM4	1727	2964	-1059	178
IDM5	253	-830	-1199	116
IDM6	1298	1566	153	115
IDM7	-12	-410	-398	0
Total	19660	46761	24278	2822

middle rows of eq. (2.1)). Finally, the *Robust cost* column contains the decrease in the total expected incomes of the *Incomes* column, and represents the most unfavorable outcome of the price deviations, consequently having the most significant impact on reducing the overall benefit of the optimization problem (last row of eq. (2.1)). Thus:

$$\text{Profit} = \text{Incomes} - \text{Operation cost} - \text{Robust cost} \quad (4.1)$$

This notation will be used in the economic analyses presented in the remainder of this chapter.

In Table 4-8, in the DAM row, the benefit and costs come from the traded energy in the DAM only but the optimization problem is solved for DAM+SRM snapshot. In the SRM row, the benefit and cost come from the traded reserve in the SRM only but the optimization problem is solved for SRM+IDM1 snapshot. Each IDM row shows the changes in the profit and costs in each IDM. The total row represents the profit and costs of DVPP in all sequential energy and reserve markets. The DVPP profit in the DAM is negative due to the fact that most of DVPP production is consumed by its demands, although the DVPP is energy seller in most of the hours. The profit in the SRM is 20275 € that comes from selling both up/down reserve. The negative operation cost (-1348 €) is due to lower production of DVPP units compared to previous market sessions. The negative amount for incomes, for example in IDM5 and IDM7, represents the case that the DVPP buys electricity in most of hours. The main profit of IDMs is related to IDM1 that has higher liquidity compared to other IDMs.

4.3.2 Case 1: Southern-Europe System – Sunny Day

This section mainly includes the cost analysis of different market solutions (the aggregation level of DVPP) in different energy and reserve markets for different robustness strategies and for sunny day weather condition in Southern-Europe Network. The profit, incomes, operation cost, and robust cost are calculated and compared for different scenarios (see eq. (4.1)). The scenarios of this case are defined in Table 4-5.

4.3.2.1 Scenario 1.1: No Aggregation Allowed

In Scenario 1.1, it is assumed that each unit separately participates in the different electricity markets. It emulates the scenario where the System Operator does not allow units to be aggregated and conform a single bidding unit. This scenario is considered as the base case for comparison with other scenarios.

Table 4-9 shows the profit and different costs related to hydro power plant in the DAM+SRM problem for optimistic, balanced, and pessimistic market participation strategies. We recall that such market participation strategies are defined based on the robustness strategy of the System Operator, i.e., on the robustness budget chosen for the optimization algorithm (see Table 4-4). The profit and costs for the hydro power plant are calculated assuming that the unit submits both energy and reserve offers in the DAM+SRM scenario. By considering the price uncertainty, the profit that the hydro power plant can obtain in the balanced and pessimistic cases is reduced by 8% and 19% compared to the optimistic case, respectively. The operation cost in the pessimistic case is reduced to 6163 €, which results from the lower production with respect to the optimistic case.

Table 4-9 Scenario 1.1 - Hydro power plant profit and costs in the DAM+SRM session for optimistic, balanced, and pessimistic cases

Robustness strategy	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic case	26294	32549	6255	0
Balanced case	24101	32419	6222	2096
Pessimistic case	21368	32230	6163	4699

Table 4-10 shows the profit and costs related to biomass power plant in the DAM+SRM session for optimistic, balanced, and pessimistic cases. The profit that biomass power plant can obtain in the balanced and pessimistic cases is reduced by 14% and 28% compared with the optimistic case, respectively. The biomass profit reductions are higher than those of the hydro power plant since the biomass unit has higher operation costs.

Tables 4-11 – 4-13 show the profit and different costs related to wind farm in all market windows for optimistic, balanced, and pessimistic cases, respectively. For the sake of conciseness and improve readability, Tables 4-11 provides a comprehensive display of the results of all market windows. However, in subsequent tables, it has been opted for brevity by aggregating the economic indices of all IDMs. The operation cost can have negative values since the change compared to previous market session is calculated. The total values represent the total profit or costs from participation in all markets.

Table 4-10 Scenario 1.1 - Biomass power plant profit and costs in the DAM+SRM session for optimistic, balanced, and pessimistic cases

Robustness strategy	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic case	3475	7434	3959	0
Balanced case	2989	7235	3827	419
Pessimistic case	2512	6012	2956	544

The total profit of wind farm for optimistic, balanced, and pessimistic cases are 6364€, 5657€, and 4957€, respectively. This is expected, as more severe robustness strategies imply less incomes and higher robust costs. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 28%, 34%, and 39%, respectively. For the optimistic case, the profit that comes from DAM, SRM, and all IDMs compared to the total profit are 75%, 19%, and 6%, respectively. For the balanced case, these proportions are 67%, 18%, and 15%, respectively. Finally, for the pessimistic case, these proportions are 59%, 17%, and 24%, respectively. Therefore, as more severe robustness strategy is considered, the wind farm prefers to move its energy bids from the DAM to the IDMs, as less forecast errors are expected in the IDMs since the forecasted value is closer to the delivery time.

Table 4-11 Scenario 1.1 - Wind farm profit and costs in different electricity markets for optimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	4788	6583	1796	0
SRM	1223	1164	-59	0
IDM1	499	709	210	0
IDM2	-131	-186	-56	0
IDM3	147	213	65	0
IDM4	3	13	10	0
IDM5	20	33	13	0
IDM6	98	135	37	0
IDM7	-283	-474	-191	0
Total	6364	8189	1826	0

Table 4-12 Scenario 1.1 - Wind farm profit and costs in different electricity markets for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	3820	5776	1523	433
SRM	1003	1164	61	100
IDM1-IDM7	834	1321	345	142
Total	5657	8261	1929	675

Table 4-13 Scenario 1.1 - Wind farm profit and costs in different electricity markets for pessimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	2947	4980	1343	690
SRM	844	1131	97	190
IDM1-IDM7	1166	1950	508	277
Total	4957	8061	1948	1157

A similar analysis is next presented for the two solar PV plants in Tables 4-14 – 4-19, which show the profit and different costs related to Solar PV1 and PV2 for the different markets and for the three considered robustness strategies, namely optimistic, balanced, and pessimistic cases.

The total profit of Solar PV1 for optimistic, balanced, and pessimistic cases are 16079€, 12856€, and 10740€, respectively. The proportion of total operation cost to total profit for the above cases are 15%, 18%, and 21%, respectively, which are lower than these proportions for wind farm in the same cases. Similar numbers are obtained for the PV2 unit. This is due to the fact that operation cost of solar PV units are lower than those of the wind farm.

For the PV1 unit, in the optimistic case, the profit that comes from DAM, SRM, and all IDMs compared to the total profit are 64%, 18%, and 18%, respectively. For the balanced case, these proportions are 53%, 20%, and 27%, respectively. Finally, for the pessimistic case, these proportions are 39%, 20%, and 41%, respectively. For the PV2 unit, these proportions are 72%, 18%, and 10%, for the optimistic case; 62%, 19%, and 19% for the balanced case; and 48%, 17%, and 35% for the pessimistic scenario. A same trend as for the wind farm unit is observed here since as more conservative robustness strategy is considered, the solar PV units prefer to move its energy bids from the DAM to the IDMs as the forecast data is expected to be more accurate in the IDMs.

Table 4-14 Scenario 1.1 - Solar PV1 profit and costs in different electricity markets for optimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	10367	12300	1933	0
SRM	2861	2957	95	0
IDM1-IDM7	2851	3308	457	0
Total	16079	18565	2485	0

Table 4-15 Scenario 1.1 - Solar PV1 profit and costs in different electricity markets for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	6797	10481	1663	2020
SRM	2626	2892	58	207
IDM1-IDM7	3433	4581	628	521
Total	12856	17954	2349	2748

Table 4-16 Scenario 1.1 - Solar PV1 profit and costs in different electricity markets for pessimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	4188	8622	1364	3071
SRM	2111	2583	77	395
IDM1-IDM7	4441	6116	811	864
Total	10740	17321	2252	4330

Table 4-17 Scenario 1.1 - Solar PV2 profit and costs in different electricity markets for optimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	10432	12277	1845	0
SRM	2635	2626	-9	0
IDM1-IDM7	1420	1649	229	0
Total	14487	16552	2065	0

Table 4-18 Scenario 1.1 - Solar PV2 profit and costs in different electricity markets for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	7633	10786	1588	1565
SRM	2353	2555	21	181
IDM1-IDM7	2384	3198	451	362
Total	12370	16539	2060	2108

Table 4-19 Scenario 1.1 - Solar PV2 profit and costs in different electricity markets for pessimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	4699	8913	1346	2868
SRM	1732	2278	177	369
IDM1-IDM7	3425	4685	646	615
Total	9856	15876	2169	3852

Tables 4-20 – 4-22 show the profit and different costs related to STU in the DAM, SRM, and seven IDMs for optimistic, balanced, and pessimistic cases, respectively. The total profit of STU for optimistic, balanced, and pessimistic cases are 17254€, 13656€, and 9484€, respectively. The proportion of total operation cost to total profit for the above cases are 59%, 54%, and 40%, respectively. The above proportions have higher values than solar PVs and wind farm since the operation cost of STU is higher.

For the optimistic case, the profit from DAM, SRM, and all IDMs compared to the total profit are 84%, 13%, and 3%, respectively. For the balanced case, these proportions are 77%, 19%, and 4%, respectively. Finally, for the pessimistic case, these proportions are 68%, 31%, and 1%, respectively. The significant part of STU profit comes from the DAM and SRM and the profit from the IDMs is just few percentage for above cases. The reason is that unlike ND-RESs, the STU is, to a considerable extent, dispatchable with the help of its thermal storage although its input thermal energy is uncertain.

Figures 4-23 and 4-24 show the STU traded energy and up/down SR for optimistic, balanced, and pessimistic cases that result from solving the DAM+SRM problem. The STU starts producing energy after hour 9 for all strategies. The production of STU in the optimistic case is much higher than balanced and pessimistic cases between hours 9-17. This is due to lower thermal energy input for balanced and pessimistic cases compared to optimistic case. Between hours 19-23, the output energy of STU is very similar for all cases. The reason is that the output energy of STU mainly comes from the thermal storage in these hours and it is not affected by uncertain input solar thermal energy.

The STU provides both up/down SR between hours 9-19 and 23-24 when the SR price is high in all cases. However the STU provided reserve between hours 20-22 is zero due to

Table 4-20 Scenario 1.1 - STU profit and costs in different electricity markets for optimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	14464	24379	9915	0
SRM	2245	2269	25	0
IDM1-IDM7	536	823	285	0
Total	17245	27471	10225	0

Table 4-21 Scenario 1.1 - STU profit and costs in different electricity markets for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	10534	19416	7621	1261
SRM	2608	2491	-272	155
IDM1-IDM7	514	987	84	389
Total	13656	22894	7433	1805

Table 4-22 Scenario 1.1 - STU profit and costs in different electricity markets for pessimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	6453	12239	4286	1500
SRM	2993	3079	-314	399
IDM1-IDM7	38	192	-193	348
Total	9484	15510	3779	2247

high DAM electricity price and low SRM reserve price. For the optimistic case and in hours 9-10, 12-14, and 23 the STU just sells energy in the energy market and does not offer SR. This is due to the fact that by considering exact forecast data in the optimistic case, the STU can obtain higher profit by just participation in the DAM. However, the provided energy of STU is reduced in the balanced and pessimistic cases in those hours and instead the STU provides more up/down SR in the SRM.

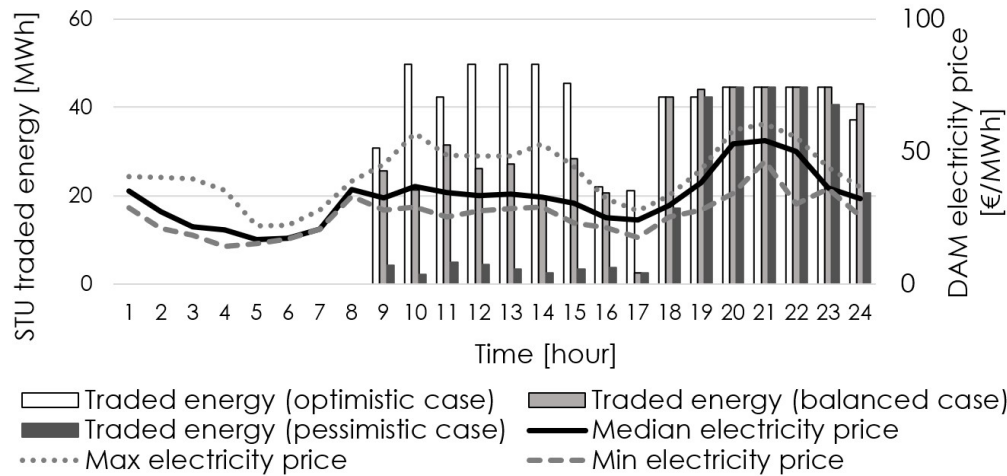


Figure 4-23 Scenario 1.1 - STU traded energy for optimistic, balanced, and pessimistic cases

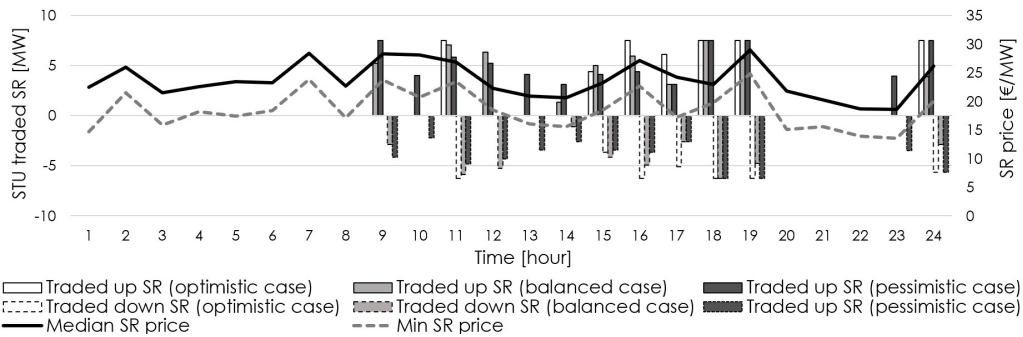


Figure 4-24 Scenario 1.1 - STU traded up/down SR for optimistic, balanced, and pessimistic cases

Figure 4-25 depicts the STU thermal storage SoC and charging/discharging power for optimistic, balanced, and pessimistic cases. The trend of charging/discharging for all cases shows some similarities. In this regard, STU thermal storage usually charges between hours 9-18 so that it reaches its maximum SoC in hour 18 and then it discharges between hours 19-24 in which the electricity price is high. However, there are significant differences between cases. For example, for the balanced case, the charging power is relatively low in hours 12 and 14 and even STU thermal storage discharges in hour 13. This is due to the fact that in these hours the uncertain parameters have higher variations compared to other hours. Moreover, STU thermal storage has high charging power in hours 10-11 and 15-17 to compensate the low charging power in hours 12-14. For the pessimistic case, the trend of charging power between hours 9-18 is smooth and is similar to optimistic case with lower values. This is due to the fact that the variation of uncertain parameters occurs in more hours than balanced case. Therefore, the charging power is reduced evenly in more hours compared to balanced case.

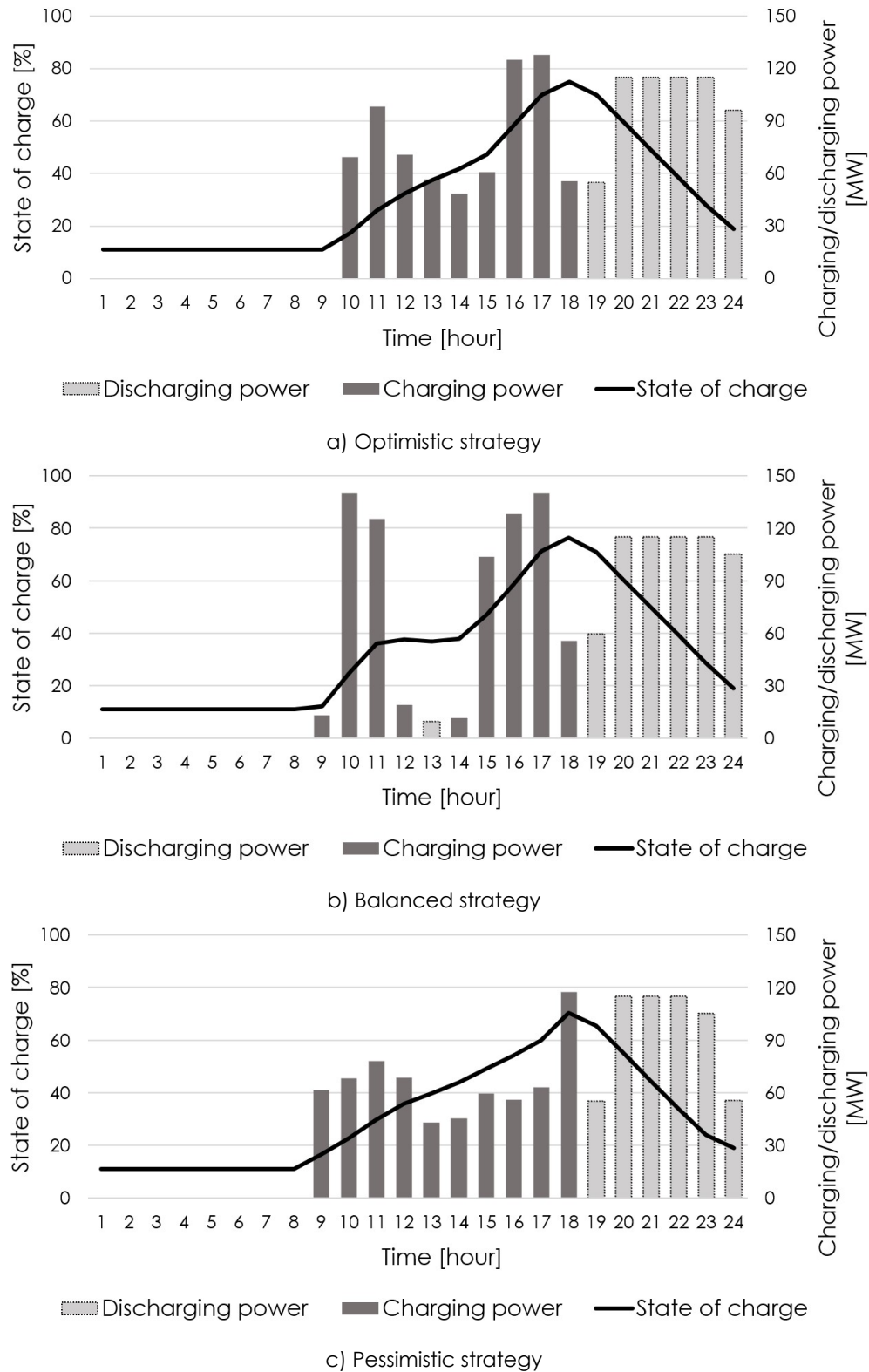


Figure 4-25 Scenario 1.1 - STU SoC and charging/discharging power for different cases

Finally, Tables 4-23 – 4-25 show the cost of industrial, airport, and residential demands, respectively, that result from solving the DAM+SRM optimization problem for the three market participation strategies. For each demand, no flexibility is considered, i.e., profile 1 is always considered, and no reserve can be provided. This implies that, in this scenario, no decision needs to be made by the demands, and the optimization problem only displays the cost of buying the energy required to feed the demands according to the worst-case scenarios defined by the selected robust uncertainty budget.

The total cost of industrial, airport, and residential demands for the optimistic case is 22090€, 28922€, and 21313€, respectively. For the balanced case, this cost is increased by 15%, 13%, and 14%, respectively, whereas for the pessimistic case these proportions are 29%, 28%, 27%, respectively, compared to the optimistic case. The similar rate of increase of demands cost indicates that the uncertainty affect all load types in more or less a similar way, which is expected.

Table 4-23 Scenario 1.1 - Industrial demand cost in the DAM for optimistic, balanced, and pessimistic cases

Robustness strategy	Total cost [€]	Robust cost [€]
Optimistic case	22090	0
Balanced case	25482	1893
Pessimistic case	28464	3651

Table 4-24 Scenario 1.1 - Airport demand cost in the DAM for optimistic, balanced, and pessimistic cases

Robustness strategy	Total cost [€]	Robust cost [€]
Optimistic case	28922	0
Balanced case	32781	2232
Pessimistic case	37091	4328

Table 4-25 Scenario 1.1 - Residential demand cost in the DAM for optimistic, balanced, and pessimistic cases

Robustness strategy	Total cost [€]	Robust cost [€]
Optimistic case	21313	0
Balanced case	24429	1804
Pessimistic case	27100	3266

4.3.2.2 Scenario 1.2: Only ND-RESs Allowed

In this section, it is assumed that only units based on stochastic RESs can be aggregated as a single bidding unit for electricity market participation purposes. Therefore, the DVPP in this section comprises the wind farm, solar PV1, solar PV2, and STU shown in Fig. 4-1. The hydro and biomass power plants plant participate in the market separately, whereas the three demand types can only buy the energy at the DAM price, as done in Scenario 1.1.

Tables 4-26 – 4-28 show the profit and different costs of the units that comprise the DVPP in the DAM, SRM, and seven IDMs for optimistic, balanced, and pessimistic cases, respectively. The total DVPP profit for the three cases are 58020 €, 49679 €, and 42549 €, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 29%, 27%, and 26%, respectively. For the optimistic case, the profit that comes from DAM, SRM, and all IDMs compared to the total profit are 67%, 20%, and 13%, respectively. For the balanced case, these proportions are 58%, 23%, and 19%, respectively. Finally, for the pessimistic case, these proportions are 46%, 24%, and 30%, respectively. Therefore, as more severe robustness strategy is considered, the DVPP prefers to move its energy bids from the DAM to the IDMs as the forecast data is closer to the power delivery, and thus more accurate in the latter.

Table 4-26 Scenario 1.2 - DVPP profit and costs in different electricity markets for optimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	38744	53360	14616	0
SRM	11688	11600	-88	0
IDM1-IDM7	7588	9769	2181	0
Total	58020	74729	16709	0

Table 4-27 Scenario 1.2 - DVPP profit and costs in different electricity markets for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	28751	44456	11820	3885
SRM	11419	11568	-574	724
IDM1-IDM7	9509	12557	1935	1112
Total	49679	68581	13181	5721

Table 4-28 Scenario 1.2 - DVPP profit and costs in different electricity markets for pessimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	19491	33412	8157	5764
SRM	10421	11238	-720	1537
IDM1-IDM7	12637	18032	3463	1931
Total	42549	62682	10900	9232

Table 4-29 compares the total profit and costs of Scenario 1.1 and 1.2 for the three robustness strategies. For Scenario 1.2, the numbers of the units that do not comprise the DVPP (hydro and biomass generation and demands) are taken from Scenario 1.1 and included here for the sake of comparison of the overall portfolio. In other words, differences in the results shown below arise from the differences between aggregating or not the stochastic sources (ND-REs and STU).

The proposed DVPP solution (scenario 1.2) can obtain, remarkably, 33%, 46%, and 22% higher profit compared to scenario 1.1 for the optimistic, balanced, and pessimistic cases, respectively. We recall that only units based on stochastic renewable sources are aggregated in this Scenario. Thus, the DVPP solution is considerably better than the solution where each unit separately participates in the market, thanks, to a great extent, to the storage capability of the STU. This is due to the fact that DVPP units can better "cover" each others uncertainty when they participate in the market as a single entity. A similar result can be obtained by comparing the robust cost of DVPP solution to Scenario 1.1. The robust cost of scenario 1.2 is 10% and 8% lower for balanced and pessimistic cases, respectively. Therefore the DVPP has higher impact than Scenario 1.1 in alleviating both energy and price uncertainties.

Table 4-29 Comparison between total profit and costs of Scenario 1.1 and 1.2 for different electricity market participation strategies

Robustness strategy	Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	1.1	11619	38435	26815	0
	1.2	15464	42387	26923	0
Balanced	1.1	-11063	28539	23820	15780
	1.2	-5923	31472	23230	14165
Pessimistic	1.1	-33738	13599	19267	28074
	1.2	-26226	19514	20019	25720

4.3.2.3 Scenario 1.3: D-RESs and ND-RESs Allowed

In this section it is assumed that D-RES and ND-RES can be aggregated to participate in energy and reserve markets as a DVPP. Therefore, the DVPP in this section comprises the hydro and biomass power plants, the wind farm, solar PV1, solar PV2, and STU of Fig. 4-1. As in Scenario 1.2 above, the three demand types can only buy the energy at the DAM price.

Tables 4-30 – 4-32 show the profit and different costs related to the DVPP (i.e., all generating units aggregated) in the DAM, SRM, and seven IDMs for optimistic, balanced, and pessimistic cases, respectively.

The total profit of DVPP for optimistic, balanced, and pessimistic cases are 93485€, 83232€, and 73488€, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 30%, 30%, and 33%, respectively. For the optimistic case, the profit that comes from DAM, SRM, and all IDMs compared to the total profit are 66%, 23%, and 11%, respectively. For the balanced case, these proportions are 59%, 25%, and 16%, respectively. Finally, for the pessimistic case, these proportions are 52%, 25%, and 23%. Therefore, as more severe robustness strategy is considered, the DVPP prefers to move its energy bids from the DAM to the IDMs as the forecast data is more accurate in the IDMs.

Table 4-30 Scenario 1.3 - DVPP profit and costs in different electricity markets for optimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	61654	85515	23860	0
SRM	21688	21318	-371	0
IDM1-IDM7	10143	14646	4505	0
Total	93485	121479	27994	0

Table 4-31 Scenario 1.3 - DVPP profit and costs in different electricity markets for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	49494	76187	20745	5948
SRM	20672	21268	-386	982
IDM1-IDM7	13066	19280	4882	1333
Total	83232	116735	25241	8263

Table 4-32 Scenario 1.3 - DVPP profit and costs in different electricity markets for pessimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	38161	64241	16256	9825
SRM	18388	20998	468	2142
IDM1-IDM7	16939	26848	7513	2395
Total	73488	112087	24237	14362

Table 4-33 compares the total profit and costs of this DVPP with the results of scenario 1.1. As for the analysis presented for Scenario 1.2 above, here the differences in the results are due to the impact of aggregating or not the generating units as a DVPP. In this case, the proposed DVPP has better even performance in terms of profit and robust cost compared to Scenario 1.2.

Table 4-33 Comparison between total profit and costs of Scenario 1.1 and 1.3 for different electricity market participation strategies

Robustness strategy	Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	1.1	11619	38435	26815	0
	1.3	21160	49154	27994	0
Balanced	1.1	-11063	28539	23820	15780
	1.3	540	39972	25241	14192
Pessimistic	1.1	-33738	13599	19267	28074
	1.3	-19167	30677	24237	25607

4.3.2.4 Scenario 1.4: RESs and Flexible Demands Allowed

In this section, which discusses the last Scenario of Case 1, it is assumed that any unit (either generation or demand) can be aggregated in the form of a DVPP to jointly participate in the Spanish electricity market. Thus, in this Scenario, the DVPP portfolio comprises all generating units from Scenario 1.3, as well as the three demands (industrial, residential and airport). In this case, the demands can also provide flexibility by allowing the possibility of choosing one out of three predefined daily consumption profiles. This choice is made by the optimization algorithm according to the worst-case realization, based on the uncertainty budget chosen for a given robustness strategy.

Tables 4-34 – 4-36 show the profit and different costs related to DVPP in the DAM, SRM, and seven IDMs for the three robustness strategies considered so far.

The total profit of DVPP for optimistic, balanced, and pessimistic cases are 25542€, 19660€, and 12146€, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 107%, 123%, and 180%, respectively. These proportions are higher than 100% since the total demand of DVPP is high and the DVPP supplies its demand by having high production which in turn leads to high operation cost of its generation units. Besides, the profit of DVPP in the DAM is -7402€, -15420€, and -26604€ for optimistic, balanced, and pessimistic cases, respectively. The reason that the profits for all cases are negative, even in the optimistic case, is that although the DVPP is energy a net energy seller in most of the hours in the DAM, the operation cost of units exceeds the profit that DVPP obtains by selling energy in the market.

Table 4-34 Scenario 1.4 - DVPP profit and costs in different electricity markets for optimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	-7402	17172	24573	0
SRM	20910	20066	-843	0
IDM1-IDM7	12034	15814	3779	0
Total	25542	53052	27509	0

Table 4-35 Scenario 1.4 - DVPP profit and costs in different electricity markets for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	-15420	7196	21996	620
SRM	20275	19846	-1348	918
IDM1-IDM7	14805	19719	3630	1284
Total	19660	46761	24278	2822

Table 4-36 Scenario 1.4 - DVPP profit and costs in different electricity markets for pessimistic case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	-26604	6717	18695	1192
SRM	19890	20100	-1829	2039
IDM1-IDM7	18860	12561	5066	2069
Total	12146	39378	21932	5300

Table 4-37 compares the total profit and costs of Scenario 1.4 with those of Scenario 1.1. The proposed DVPP solution obtains better results in all cases. It can also be observed that the DVPP obtains positive profits even in the pessimistic case. Considering the demand flexibility and the possibility of selecting different demands profiles has a great impact in this regard. Note that the cost of selecting a load profile different from profile 1 (i.e., the default profile) is considered null in these results. By considering the cost of selecting demand cost, the DVPP profit will consequently be lower. However, the identification of realistic values of this cost for each load type is beyond the scope of this work. Finally, the robust cost of Scenario 1.4 is 82% and 81% lower than robust cost of Scenario 1.1 for balanced and pessimistic cases, respectively. The majority of such robust cost reduction comes from the demand flexibility.

Table 4-37 Comparison between total profit and costs of Scenario 1.1 and 1.4 for different electricity market participation strategies

Robustness strategy	Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	1.1	11619	38435	26815	0
	1.4	25542	53052	27509	0
Balanced	1.1	-11063	28539	23820	15780
	1.4	19660	46761	24278	2822
Pessimistic	1.1	-33738	13599	19267	28074
	1.4	12146	39378	21932	5300

4.3.2.5 Concluding Remarks for Case Study 1

This section collects the main results of the four scenarios considered in Case Study 1, and are shown in Table 4-38 which compares the profit in DAM, SRM, and total *daily* profit (including DAM, SRM, and all IDMs) .

A clear trend can be observed. The total profit is increased by considering the possibility of aggregation of more assets in the DVPP. For example, the total profit in the optimistic case is increased by 33%, 82%, and 120% in scenario 1.2 (only ND-REss aggregation), 1.3 (aggregation of generating units of any type), and 1.4 (generation and demands aggregation) compared to scenario 1.1 (no aggregation), respectively. These proportions are even increased when more conservative market participation strategies are considered. The results show the superiority of DVPP by considering the aggregation of all units compared to other solutions for all robustness strategies.

The profit from DAM in all cases are negative due to the relatively large size of the demands in the portfolio, and to the operation costs of the DVPP generation units. The profit in the DAM for scenarios 1.2 and 1.3 in the optimistic case, and for scenario 1.2 in the balanced case is decreased compared to scenario 1.1. This is due to the fact that it is possible for DVPP to arbitrage between DAM and SRM. Therefore, these reductions in DAM profit is compensated by obtaining more profit from the SRM.

Table 4-38 Comparison between profit of different scenarios in Case Study 1

Market condition	Profit optimistic [k€]			Profit balanced [k€]			Profit pessimistic [k€]		
	DAM	SRM	Total	DAM	SRM	Total	DAM	SRM	Total
No coord.	-9.4	15.9	11.6	-33.3	15.1	-11.1	-56.6	13.8	-33.7
Only ND-REss	-10.7	18.6	15.5	-33.4	18.0	-5.9	-55.4	16.6	-26.2
ND-REss+D-REss	-10.7	21.7	21.1	-33.2	20.7	0.5	-54.5	18.4	-19.2
Gen. + demand	-7.4	20.9	25.5	-15.4	20.3	19.7	-26.6	19.9	12.1

Other concluding remarks are listed below:

- When only stochastic generating units (ND-REss and STUs) conform the DVPP (Scenario 1.2), the total profit compared to Scenario 1.1 is increased between 20-50% for robustness strategies. This scenario shows that only by aggregation of units that have uncertain production, the profit of DVPP can increase in some degree.
- In Scenario 1.3, it is assumed that both D-REss and ND-REss are aggregated as a DVPP. The total profit in this case compared to Scenario 1.1 is increased between 40-105% for strategies. Results show that DVPP units in this case can better cover the uncertainty of stochastic sources. In other words, the D-REss can substantially help the ND-REss to cover their uncertain production.
- In Scenario 1.4, it is assumed that both renewable generation and flexible demands aggregation in form of a DVPP is allowed. The total profit in this scenario compared to scenario 1.1 is increased between 120-280% for all optimistic, balanced, and pessimistic cases. In this scenario, adding the flexibility of demand leads to a great increase in the overall profit. However, the cost of selecting different demands is assumed zero in this case study. By considering a cost for selecting different demand profiles, the profit can decrease in some degree.

4.3.3 Case 2: Southern-Europe System – Cloudy Day

In Case 1, the economic viability of a DVPP in the Spanish system is studied for favorable weather conditions. This section evaluates such viability but considering that the system is subject to adverse conditions, i.e., in a cloudy day, and with potentially higher forecast errors. Again, the profit, incomes, operation costs, and robust costs are calculated and compared for different scenarios. The scenarios of this case are defined in Table 4-5. Only balanced robustness strategy is considered in the Scenarios discussed below.

4.3.3.1 Scenario 2.1: No Aggregation Allowed

In Scenario 2.1, it is assumed that each unit separately participates in different electricity markets. With respect to Scenario 1.1, the different weather conditions only affect the solar PVs and STU production, thus the results for other DVPP units are the same as those of Scenario 1.1 in Section 4.3.2.1 above.

Tables 4-39 – 4-41 show the profit and different costs for balanced case in the cloudy day related to solar PV1, solar PV2, and STU, respectively. The results show that the total profit of solar PV1, solar PV2, and STU is reduced compared to sunny day Scenario 1.1, down to 9660€, 7718€ and 8972€ respectively. The total profit of these units compared to sunny day Scenario 1.1 is thus reduced by 25%, 38%, and 34%, respectively.

Table 4-39 Scenario 2.1 - Solar PV1 profit and costs in different electricity markets for balanced case in the cloudy day

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	4902	7691	1218	1571
SRM	1840	2128	146	142
IDM1-IDM7	2918	3653	474	261
Total	9660	13472	1838	1974

Table 4-40 Scenario 2.1 - Solar PV2 profit and costs in different electricity markets for balanced case in the cloudy day

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	4105	6398	980	1314
SRM	1529	1716	34	153
IDM1-IDM7	2084	2611	350	176
Total	7718	10725	1364	1643

Table 4-41 Scenario 2.1 - STUs profit and costs in different electricity markets for balanced case in the cloudy day

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	4866	8130	2546	718
SRM	2525	2548	-163	186
IDM1+IDM7	1581	2824	941	301
Total	8972	13502	3324	1205

4.3.3.2 Scenario 2.2: Only ND-RESs Allowed

In this section, it is assumed that only ND-RESs and STU are aggregated and can participate in different energy and reserve markets as a DVPP. Therefore, the DVPP in this section includes the wind farm, solar PV1, solar PV2, and STU of Fig. 4-1 for the cloudy day. As for Scenario 1.2, the hydro and biomass power plants, as well as the three loads participate in the market separately.

Table 4-42 shows the profit and costs of the units that comprise the DVPP in the DAM, SRM and seven IDMs. The results show that the total profit of the proposed DVPP in the cloudy day is 36652€, which is reduced by 26% compared to Scenario 1.2 for sunny day.

Table 4-43 compares the profit and costs of all units in the portfolio (comprising the DVPP or not) for Scenarios 2.1 and 2.2. The proposed DVPP solution can obtain 20% higher profit compared to scenario 2.1. This increase of profit is less than the 46% increase observed in favorable weather conditions (Scenarios 1.1 and 1.2). This is due to the fact that the forecast bounds of ND-RESs and STU have lower values and variations in the cloudy day compared to sunny day.

Table 4-42 Scenario 2.2 - DVPP profit and costs in different electricity markets for balanced case in the cloudy day

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	18221	26269	5556	2492
SRM	9428	9871	-159	601
IDM1-IDM7	9003	12403	2573	827
Total	36652	48543	7970	3920

Table 4-43 Scenario 2.2 - Comparison between profit and costs of the whole portfolio in Scenarios 2.1 and 2.2 for balanced case

Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
2.1	-23595	8851	18504	13941
2.2	-18950	11434	18019	12364

4.3.3.3 Scenario 2.3: D-RESs and ND-RESs Allowed

This Section mirrors Scenario 1.3 but for adverse weather conditions, i.e., it considers a DVPP comprising any renewable-based generating unit (both D-RES and ND-RES). As in Scenario 2.2 above, the three demand types can only buy the energy at the DAM price.

Table 4-44 shows the profit and costs of the DVPP units in the different markets for a balanced robustness strategy. Results show that the total profit of the DVPP in with adverse weather conditions is 70188€, which is reduced by 16% with respect to Scenario 1.3 (sunny day).

Table 4-45 compares the economic results of Scenarios 2.1 and 2.3. The proposed DVPP solution can obtain 47% higher profit compared to Scenario 2.1 (balanced case). This increase of profit for is again lower than the increase of profit of 105% in the sunny day (Scenarios 1.1 and 1.3).

Table 4-44 Scenario 2.3 - DVPPs profit and costs in different electricity markets for balanced case in the cloudy day

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	38914	57807	14428	4465
SRM	18689	19613	70	854
IDM1-IDM7	12585	19141	5525	1031
Total	70188	96561	20023	6350

Table 4-45 Scenario 2.3 - Comparison between profit and costs of the whole portfolio in Scenarios 2.1 and 2.3 for balanced case

Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
2.1	-23595	8851	18504	13941
2.3	-12505	19798	20023	12279

4.3.3.4 Scenario 2.4: RESs and Flexible Demands Allowed

Finally, the possibility of aggregating both generating and flexible demand units as a DVPP is studied.

Tables 4-46 and 4-47 show the profits and costs of the DVPP in the different market windows (balanced strategy), and the corresponding comparison with results from Scenario 2.1. respectively. The total DVPP profit in the cloudy day is 4756€, which is 76% lower than that obtained in scenario 1.4 for sunny day. This profit is still 120% higher than in Scenario 2.1. However, this rate of increase of profit is lower for the cloudy day than for the sunny day (278%).

Table 4-46 Scenario 2.4 - DVPPs profit and costs in different electricity markets for balanced case in the cloudy day

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	-28020	-10816	16480	725
SRM	18941	18083	-1656	797
IDM1-IDM7	13835	18114	3441	838
Total	4756	25381	18265	2360

Table 4-47 Scenario 2.4 - Comparison between total profit and costs of Scenarios 2.1 and 2.4 for balanced case

Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
2.1	-23595	8851	18504	13941
2.4	4756	25381	18265	2360

4.3.3.5 Concluding Remarks for Case Study 2

In this section, the main results of all scenarios in case study 2 are compared; then the main remarks of case study 2 are presented. Table 4-48 compares the profit in DAM, SRM, and total profit (including DAM, SRM, and all IDs) for all scenarios of case study 2 for balanced case. Generally, the total profit is increased by considering the possibility of aggregation of more assets in the DVPP. The total profit in the balanced case is increased by 20%, 47%, and 120% in scenario 2.2 (only ND-RESs aggregation), 2.3 (ND-RESs and D-RESs aggregation), and 2.4 (generation and demands aggregation) compared to scenario 2.1 (no coordination), respectively. The DAM profit in all cases are negative due to high amount of demand which in turn leads to high operation cost for DVPP generation units. The SRM profit in the balanced case is increased by 19%, 39%, and 40% in scenario 2.2 (only ND-RESs aggregation), 2.3 (ND-RESs and D-RESs aggregation), and 2.4 (generation and demands aggregation) compared to scenario 2.1 (no coordination), respectively. Therefore, the results show the superiority of DVPP by considering the aggregation of all units compared to other solutions in the cloudy day.

Table 4-48 Comparison between profits (in k€) of different scenarios in Case Study 2 and Case Study 1 for balanced conditions

Market condition	Case Study 2			Case Study 1		
	DAM	SRM	Total	DAM	SRM	Total
No coord.	-44.5	13.5	-23.6	-33.3	15.1	-11.1
Only ND-RESs	-43.9	16.0	-18.9	-33.4	18.0	-5.9
ND-RESs+D-RESs	-43.8	18.7	-12.5	-33.2	20.7	0.5
Gen. + demand	-28.0	18.9	4.76	-15.4	20.3	19.7

The summary and main conclusions of case study 2 are as bellow:

- The profit and costs of units that are affected by cloudy weather conditions with the assumption of separate participation in different energy and reserve markets is provided in Scenario 2.1 as a base case. The results show that total profit of solar PVs and STU is decreased compared to sunny day due to lower production of these units.
- The total profit of Scenario 2.2 compared to Scenario 2.1 is increased by 20% for balanced case. However, the 20% increase of profit for cloudy day is less than the increase of profit of 46% in the sunny day (by comparing the profit of scenarios 1.1 and 1.2) due to the lower values and variations of cloudy day forecast data.
- The total profit in Scenario 2.3 compared to Scenario 2.1 is increased by 47% for balanced case. The results show that DVPP units in this case can better cover the uncertainty of each others. Specially, the D-RESs can substantially help the ND-RESs to cover their uncertain production.
- The total profit in Scenario 2.4 compared to Scenario 2.1 is increased by 120% for balanced case. The results show that adding the flexibility of demand and the possibility of selecting different profile of demands leads to substantially more profit for DVPP. Again, no cost associated to the selection of different demand profiles is considered in this case.

4.3.4 Case 3: Southern-Europe System – Electrochemical Storage-based Alternative Solutions

In this section the profit and costs analysis of BESs with different capacities are presented. The objective is to find the capacity of BES required to reach a similar profit as DVPP solutions. In this regard, first, the profit and different costs of DVPP, which includes ND-RESs and STU, is obtained and compared with no aggregation solutions. Then, the extra benefit that DVPP can obtain is considered to find the capacity of BES. The comparison is done for different robustness strategies and weather conditions in Southern-Europe network. No demand flexibility is considered in the scenarios discussed in this Section.

4.3.4.1 Scenario 3.1: Optimistic case, Sunny Day

Table 4-49 shows the profit and different costs of the different units of the portfolio in the DAM+SRM optimization problem for the optimistic case. The table compares cases for which no aggregation is allowed, and when the DVPP comprises ND-RESs and STUs. For simplicity, results are obtained by assuming that units or DVPP bid both the energy and reserve obtained from the DAM+SRM optimization problem, i.e., there is not another subsequent problem for bidding reserve (e.g., SRM+IDM1). According to the table, the DVPP can obtain $7769\text{€} - 6342\text{€} = 1427\text{€}$ more profit than no aggregation solution. This extra profit will be used to determine the capacity of the BES required to get similar results.

Table 4-49 Scenario 3.1 - Units profit and costs in the DAM+SRM problem

Units	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Hydro plant	26294	32549	6255	0
Biomass plant	3475	7434	3959	0
Wind farm	5793	7589	1796	0
Solar PV1	13324	15257	1933	0
Solar PV2	13058	14903	1845	0
STU	16723	26637	9915	0
Industrial demand	-22090	-22090	0	0
Airport demand	-28922	-28922	0	0
Residential demand	-21313	-21313	0	0
Total	6342	32044	25703	0
DVPP	7769	32599	24830	0

The data of a 1 MWh module of BES is provided in Table 4-2. Several BESs modules can then be aggregated to reach a BES with a specific capacity. In this Scenario 3.1, a BES with 16 MWh capacity is required to reach a similar profit (1455€) to the DVPP).

Figure 4-26 shows the 16 MWh BES traded energy and up/down SR for optimistic case. The BES is energy seller in hours 1-2, 4, 8, 10-13, 15, 18, 20-22, and 24 and in other hours buys

electricity from the market. The BES sells/buys less energy than its discharging/charging power of 8MW in most of the hours to be able to provide reserve. The BES prefers to provide about 1 MW up reserve in most of the hours.

Figure 4-26 represents the 16 MWh BES SoC and charging/discharging power for optimistic case. The SoC of BES has two peaks between hours 5-9 and 17-20. In these hours, the BES usually charges energy to be able to provide energy in the hours for which the electricity price is high.

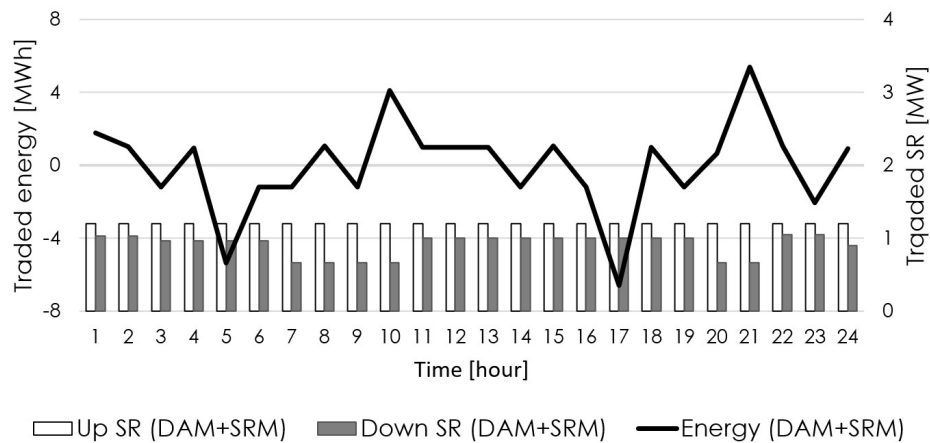


Figure 4-26 Scenario 3.1 - BES traded energy and SR

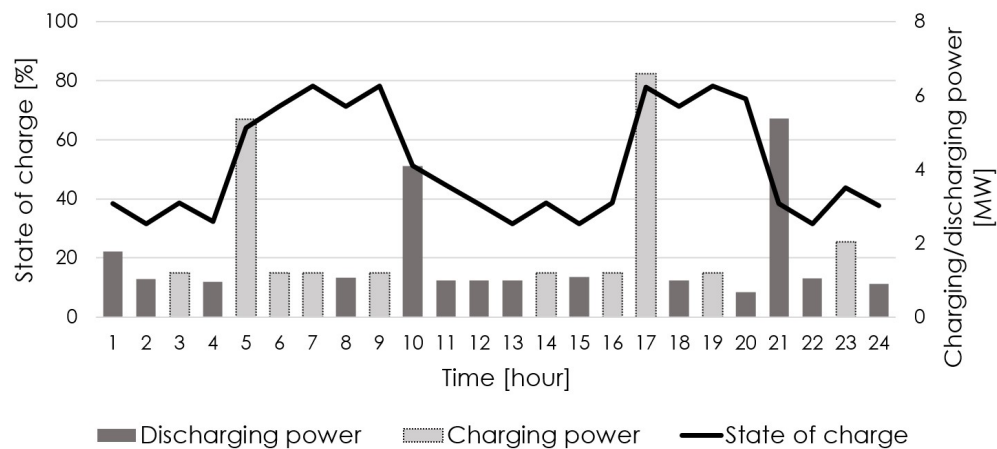


Figure 4-27 Scenario 3.1 - BES SoC and charging/discharging power

4.3.4.2 Scenario 3.2: Balanced Case, Sunny Day

Table 4-50 shows the profit and different costs of the different units, the summation of profit and different costs for all units, and the profit and different costs of these units when ND-RESs and STUs are aggregated as a DVPP in the DAM+SRM problem considering balanced robustness budget. According to the results, the DVPP can reduce by 2551€ the expenses compared to the no aggregation scenario. This value is 79% higher than the extra profit from Scenario 3.1. Therefore, a bigger BES is needed to obtain a similar result from the market in this case.

Table 4-50 Scenario 3.2 - Units profit and costs in the DAM+SRM problem

Units	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Hydro plant	24101	32419	6222	2096
Biomass plant	2989	7235	3827	419
Wind farm	4725	6781	1523	533
Solar PV1	9535	13438	1663	2239
Solar PV2	10065	13412	1588	1760
STU	12724	21743	7621	1398
Industrial demand	-25482	-23588	0	1893
Airport demand	-32781	-30549	0	2232
Residential demand	-24429	-22625	0	1804
Total	-18553	18266	22444	14374
DVPP	-16002	18929	21869	13060

In this scenario, a 30 MWh BES is needed to reach 2530€ savings. Figure 4-28 represents the 30 MWh BES traded energy and up/down SR for balanced case. The BES sells energy in hours 1-2, 4, 8-13, 15, 19-22, and 24, and buys electricity from the market in the remaining periods. The BES chooses to provide about 2 MW up reserve in most of the hours.

Figure 4-29 shows the 30 MWh BES SoC and charging/discharging power for balanced case. The SoC of BES has two peaks between hours 5-7 and and 16-19. Although the BES SoC is more or less similar to Scenario 3.1, although some differences between charging/discharging pattern due to considering the uncertainty.

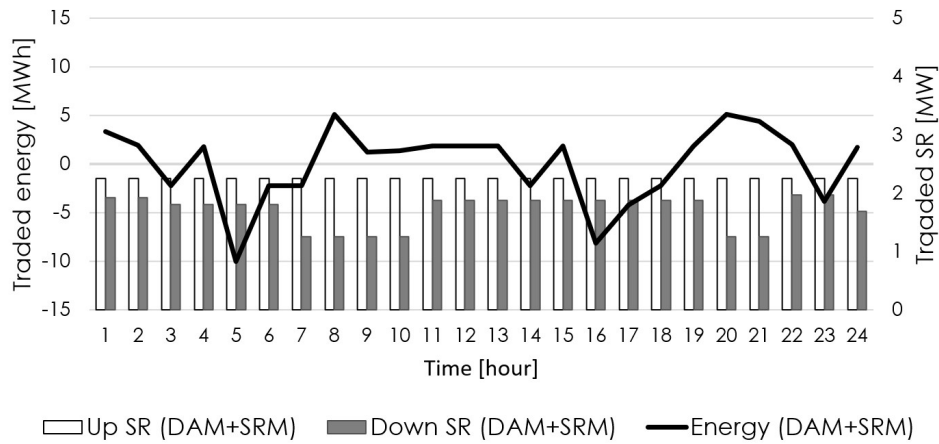


Figure 4-28 Scenario 3.2 - BES traded energy and SR

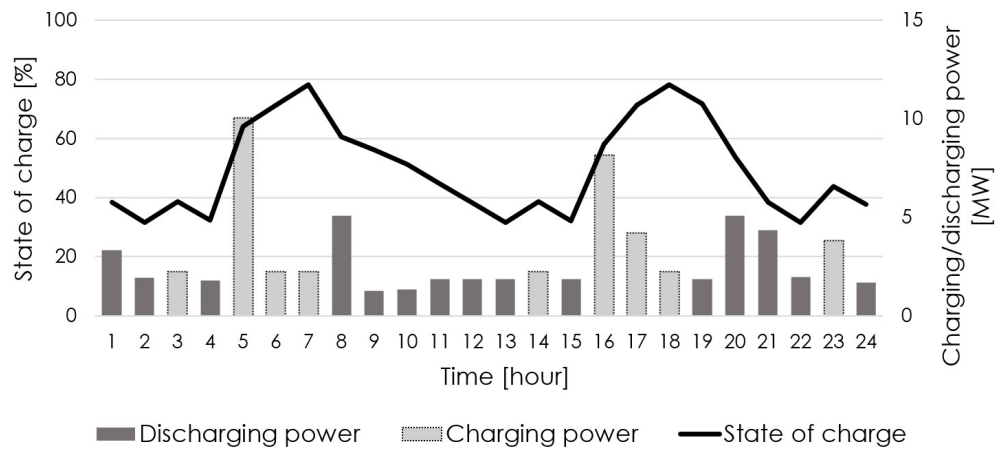


Figure 4-29 Scenario 3.2 - BES SoC and charging/discharging power

4.3.4.3 Scenario 3.3: Pessimistic Case, Sunny Day

Table 4-51 shows the results for a similar problem as for Scenarios 3.1 and 3.2 above, but considering pessimistic robustness strategy. It can be seen that the DVPP can reduce the overall expenses by 3276€. This amount is 130% higher than the extra profit from Scenario 3.1, and 28% higher than the savings from Scenario 3.2. Therefore, a bigger BES compared to scenarios 3.1 and 3.2 is now required to obtain similar results.

In this scenario, a BES with 43 MWh capacity results in 3268€ savings, fairly close to the 3276€ from the DVPP. Figure 4-30 represents the 43 MWh BES traded energy and up/down SR for balanced case, whereas the SoC and charging/discharging powers are depicted in Fig. 4-30. Again, similar trends, but with higher energy/power, are observed with respect to previous scenarios.

Table 4-51 Scenario 3.3 - Units profit and costs in the DAM+SRM problem

Units	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Hydro plant	21368	32230	6163	4699
Biomass plant	2512	6012	2956	544
Wind farm	3812	6030	1343	875
Solar PV1	6664	11579	1364	3552
Solar PV2	6886	11540	1346	3308
STU	9065	15247	4286	1896
Industrial demand	-28464	-24814	0	3651
Airport demand	-37091	-32764	0	4328
Residential demand	-27100	-23834	0	3266
Total	-42348	1226	17458	26119
DVPP	-39072	2063	17276	23861

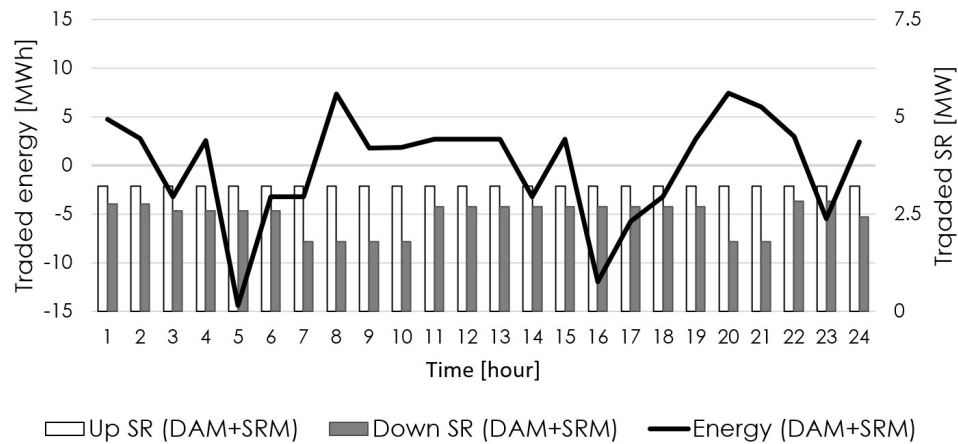


Figure 4-30 Scenario 3.3 - BES traded energy and SR

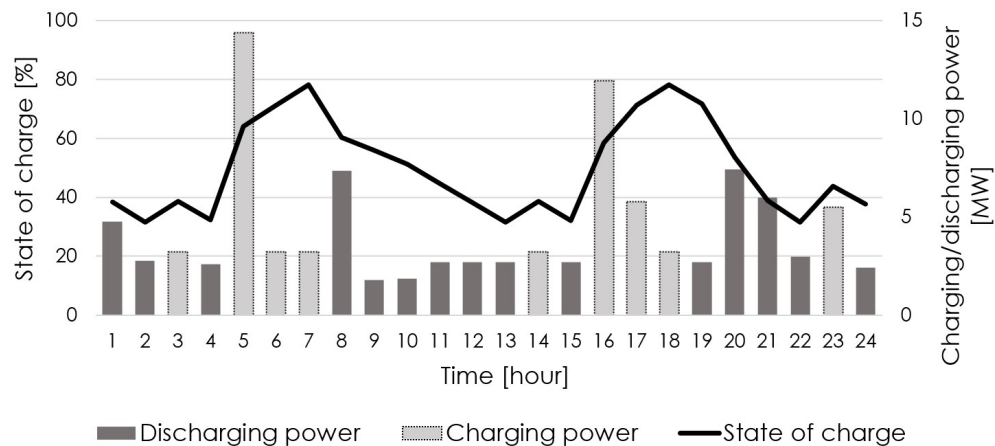


Figure 4-31 Scenario 3.3 - BES SoC and charging/discharging power

4.3.4.4 Scenario 3.4: Balanced Case, Cloudy Day

Finally, an analysis similar to that of Scenario 3.2, but for adverse weather conditions, is carried out, and results are shown in Table 4-52. In this case, the DVPP can obtain help save 3153€ with respect to the no aggregation solution, which is 24% higher than in Scenario 3.2 for a sunny day.

Table 4-52 Units profit and costs in the DAM+SRM snapshot in the cloudy day for balanced case

Units	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Hydro plant	24101	32419	6222	2096
Biomass plant	2989	7235	3827	419
Wind farm	4725	6781	1523	533
Solar PV1	6942	9895	1218	1734
Solar PV2	5642	8089	980	1467
STU	6938	10415	2546	931
Industrial demand	-25482	-23588	0	1893
Airport demand	-32781	-30549	0	2232
Residential demand	-24429	-22625	0	1804
Total	-31355	-1928	16316	13109
DVPP	-28202	-1057	15605	11539

In this scenario, the BES required to obtain a similar result (in this case 3120€) has an energy capacity of 37 MWh. The traded energy/SR, and the corresponding SoC and charging/discharging powers, are depicted in Figs. 4-32 and Fig. 4-33, respectively.

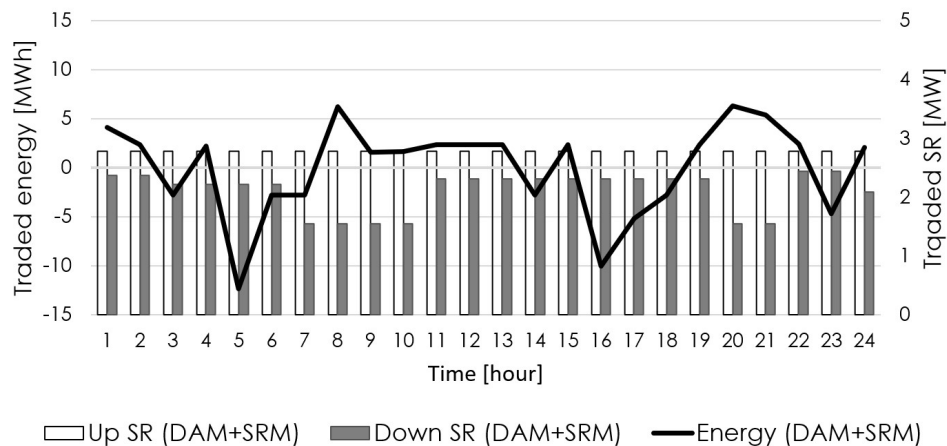


Figure 4-32 Scenario 3.4 - BES traded energy and SR

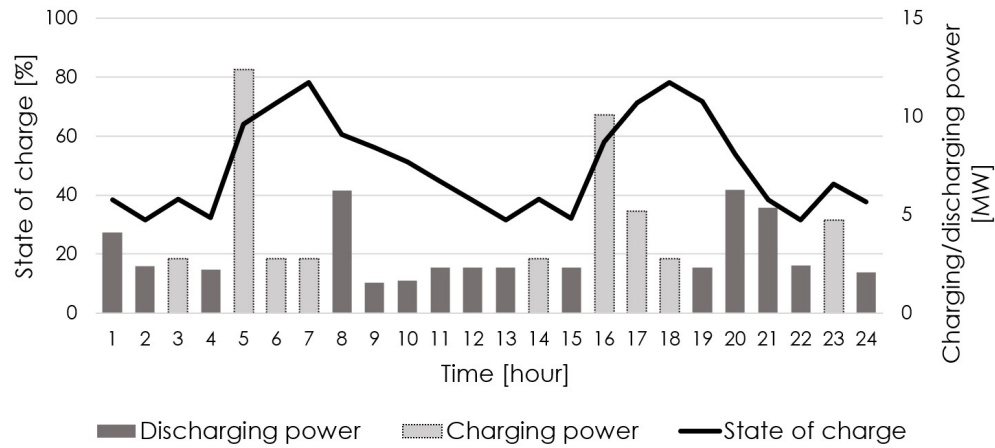


Figure 4-33 Scenario 3.4 - BES SoC and charging/discharging power

4.3.4.5 Concluding Remarks for Case Study 3

Table 4-53 compares the capacity, profit (measured as the difference between having BES or not in the overall DAM+SRM profit), and different costs of BES for optimistic, balanced, and pessimistic cases and for favorable weather conditions (Scenarios 3.1, 3.2 and 3.3, respectively). Using larger BESs leads to higher profit, but also to higher costs. Note that the robust cost comes from the energy and reserve price deviations due to uncertainty. Results for cloudy conditions and balanced strategy are also included in the Table (Scenario 3.4).

From Sections 4.3.2 and 4.3.3, it was deduced that for more severe robustness strategies, the overall profit is reduced due to the impact of the worst-case realizations of the forecast errors in the optimization problem. However, relatively, higher differences between having a DVPP or not in such profits were also observed as the robustness level increases. This leads to larger BES in order to obtain similar economic results as having the same DVPP. In other words, as more conservative strategies are adopted to deal with price and energy uncertainties, the DVPP solution becomes more relevant, which is a highly interesting result. This also applies when facing adverse weather conditions

Table 4-53 Case Study 3 - BES capacity, relative profits and costs that mimic DVPP economic results in the DAM+SRM problem

Scenario	Capacity [MWh]	Relative profit [€]	Incomes [€]	BES cost [€]	Robust cost [€]
3.1	16	1455	1521	66	0
3.2	30	2530	2816	112	174
3.3	43	3268	4035	160	606
3.4	37	3120	3473	138	215

4.3.5 Cases 4 and 5: Northern-Europe System

As discussed in Section 4.2, two more Case Studies have been analyzed. These consider a Northern-Europe system (Denmark), with different market conditions and DVPP portfolio with respect to the Spanish case. Three Scenarios are defined for each Case, which mirror the conditions of Scenarios 1.1–1.3 for Case 4, and Scenarios 2.1–2.3 for Case 5.

Again, to improve readability of this document, and for the sake of conciseness and clarity, detailed results of each Scenario are provided in Appendix B.2. In the remainder of this Section, a summary of the results and main remarks drawn from them are presented.

4.3.5.1 Concluding Remarks for Case Study 4

The main economic results from the analysis of the three Scenarios of Case 4 are collected in Table 4-54, which shows the profit in DAM and SRM (both separately and jointly), for different DVPP configurations and robustness strategies in the Denmark system with favorable weather conditions.

Generally, the total profit is increased by considering the possibility of aggregation of more assets in the DVPP. For example, the total profit in the balanced case is increased by 5.6% and 6.5% in scenario 4.2 (only ND-RESs aggregation), and scenario 4.3 (ND-RESs and D-RESs aggregation) compared to scenario 4.1 (no coordination), respectively. These proportions are increased to 15.3% and 24.4% for pessimistic case. The results show the superiority of DVPP by considering the aggregation of all units compared to other solutions for balanced and pessimistic robustness strategies. The DAM profit for all robustness strategy is increased by considering more assets in the DVPP. The DAM profit in the balanced case is increased by 9.7% and 11.5% in scenario 4.2 (only ND-RESs aggregation), and scenario 4.3 (ND-RESs and D-RESs aggregation) compared to scenario 4.1 (no coordination), respectively. These proportions are increased to 11.1% and 36.1% for pessimistic case.

Table 4-54 Comparison between profit of different scenarios in Case Study 4

Market condition	Profit optimistic [k€]			Profit balanced [k€]			Profit pessimistic [k€]		
	DAM	SRM	Total	DAM	SRM	Total	DAM	SRM	Total
No coord.	109.3	40.6	150.0	33.8	34.7	68.5	-7.6	26.7	19.1
Only ND-RESs	109.6	40.6	150.2	37.1	35.2	72.3	-6.8	28.8	22.1
ND-RESs+D-RESs	110.0	40.6	150.6	37.7	35.2	72.9	-4.8	28.7	23.8

Other remarks of case study 4 are drawn below:

- The profit and costs of different units with the assumption of separate participation in different energy and reserve markets is provided in scenario 4.1 as a base case. The results show that by adopting more severe robustness strategy, the profit of units is decreased. Besides, the main income of units comes from DAM participation for the optimistic case as it is assumed that forecast data is accurate in this case. By adopting more severe robustness strategies, the proportion of profit that comes from SRM to total profit is increased as units bid less in the energy market.

- In scenario 4.2, it is assumed that only ND-REs are aggregated as a DVPP and other units participate on their own in the market. The total profit of scenario 4.2 compared to scenario 4.1 is increased between 0 and 15% for all optimistic, balanced, and pessimistic cases. This scenario shows that only by aggregation of units that have uncertain production, the profit of DVPP can increase in some degree.
- In scenario 4.3, it is assumed that both D-REs and ND-REs are aggregated as a DVPP and participate in different energy and reserve markets. The total profit in this scenario compared to scenario 4.1 is increased between 0 and 25% for all optimistic, balanced, and pessimistic cases. The results show that DVPP units in this case can better cover the uncertainty of each others. Specially, the D-REs can substantially help the ND-REs to cover their uncertain production.

4.3.5.2 Concluding Remarks for Case Study 5

Table 4-54 shows similar results as for Case Study 4 above, but considering adverse weather conditions, and only for balanced robustness budget. In this case, the total profit is again increased by considering the possibility of aggregation of more assets in the DVPP. In particular, taking as reference the Scenario 5.1 without DVPP, overall profit sees an increase of 43% and 46% for Scenarios 5.2 (DVPP comprises only ND-REs) and 5.3 (any generating unit can be aggregated), respectively. Finally, comparing with the DVPP impact from Scenarios 4.2 and 4.3 above, The DAM profit is increased by 94% and 100%, respectively. Thus, in this case, conforming a DVPP is, in relative numbers, more beneficial in adverse conditions.

Table 4-55 Comparison between profit of different scenarios in Case Study 5

Market condition	Profit balanced [k€]		
	DAM	SRM	Total
No coord.	16.5	25.2	41.6
Only ND-REs	31.9	27.5	59.4
ND-REs+D-REs	33.0	27.6	60.5

Other remarks are as follows:

- The profit and costs of different units with the assumption of separate participation in different energy and reserve markets is provided in scenario 5.1 as a base case. The profit of wind farms in a non-windy day is significantly reduced compared to windy day.
- In scenario 5.2, it is assumed that only ND-REs are aggregated as a DVPP and other units participate on their own in the market. The total profit of scenario 5.2 compared to scenario 5.1 is increased by 43% for balanced case. Moreover, the extra profit of aggregating ND-REs in non-windy day is higher than windy day since forecast is less accurate in non-windy day.
- In scenario 5.3, it is assumed that both D-REs and ND-REs are aggregated as a DVPP and participate in the energy and reserve markets. The total profit in this scenario compared to scenario 5.1 is increased by 46% for balanced case. The results show that DVPP units in this case can better cover the uncertainty of each others so that the D-REs obtain more profit.

5 Conclusions and Future Work

This Deliverable concludes Task T5.5, presenting an in-depth examination of the economic viability of Dynamic Virtual Power Plants (DVPPs) through various synthetic, yet realistic, case studies defined in Task T5.4. The DVPP optimal bidding tool developed in Task 5.2 is used to this purpose.

The report serves a dual purpose: firstly, to validate the tool's simplicity and computational efficiency, demonstrating its seamless scalability to systems of varying sizes and complexities. Secondly, it involves a meticulous evaluation of diverse, real-world scenarios derived from actual European electricity markets, utilizing the proposed DVPP bidding framework. In the document, two regional contexts are thoroughly analyzed: a Southern-Europe region (Spain) and a Northern-Europe region (Denmark). Additionally, the report explores different weather uncertainty scenarios, considering factors like sunny and cloudy days for the Southern-Europe region, and windy and no-windy days for the Northern-Europe region, to emulate favorable and adverse weather conditions. By showcasing these contrasting scenarios, we highlight how the DVPP model can be tailored to suit distinct energy market conditions across Europe.

For instance, in the context of Spanish scenarios, simulation results reveal that well-configured and operated DVPPs can outperform electrochemical Battery Energy Storage (BESs) solutions with capacities of several tens of megawatt-hours. Notably, the DVPP configuration considered in the comparison was the *most limited* option in terms of flexibility availability, namely a stochastic, nondispatchable resource-based DVPP with an installed renewable capacity of 200 MW. Adding dispatchable resources and/or flexible demands into the DVPP would imply even larger BESs to achieve similar benefits.

The DVPP optimization tool proposed in D5.2 primarily focused on daily bidding in electricity markets. It considered a fixed DVPP portfolio, where a predetermined set of units acted as a single market participation entity. While this approach provided valuable insights into the DVPP's immediate market responses, it had limitations, particularly the lack of consideration for longer-term planning and strategic decision-making regarding the optimal DVPP configuration.

In this regard, this Task proposes an upgrade to the DVPP model, expanding its focus beyond daily bidding with a fixed portfolio. Instead, the updated model embraces a broader perspective, encompassing longer time horizons of several months. This extension enables DVPP operators to proactively adapt their strategies to capitalize on evolving market dynamics and changing conditions, by optimally selecting the best DVPP portfolio that meets all regulatory requirements.

In the last Task in this Work Package, T5.7, recommendations and policy directives based on the established and validated results of the market participation and RTO tools presented in Deliverables D5.5 and D5.6, respectively, will be proposed.

6 References

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Annex

A Uncertain Data Profiles

In this Appendix, the time series of the profiles of the uncertain quantities used as inputs of the DVPP optimization tool in the simulations presented in Chapter 4 are shown. These include the profiles of the stochastic renewable sources (solar and wind generation), the loads consumption, and the electricity market prices (DAM, SRM and IDM).

Solar Generation in the DAM

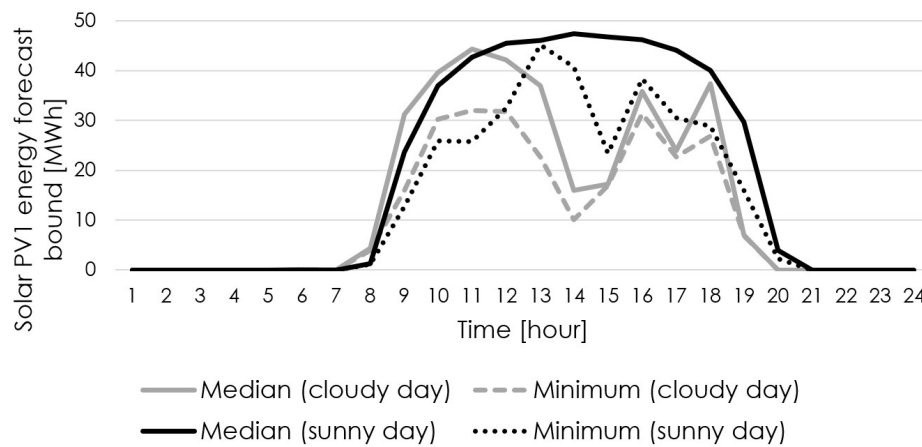


Figure A-1 Solar PV1 energy forecast bounds

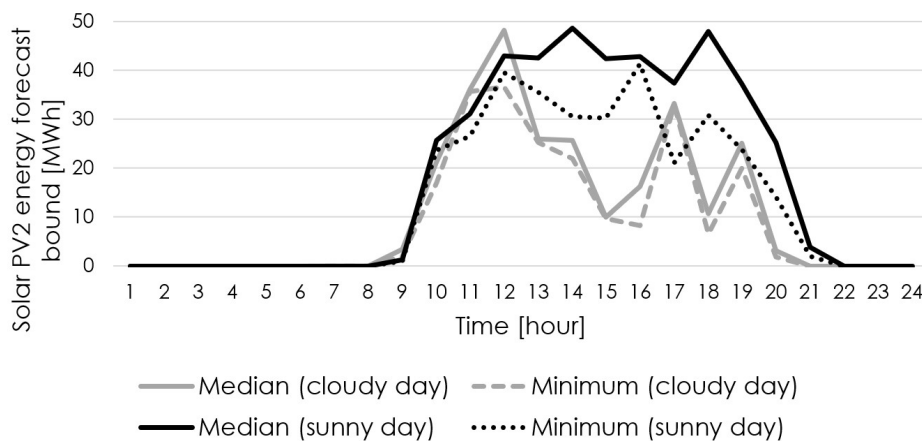


Figure A-2 Solar PV2 energy forecast bounds

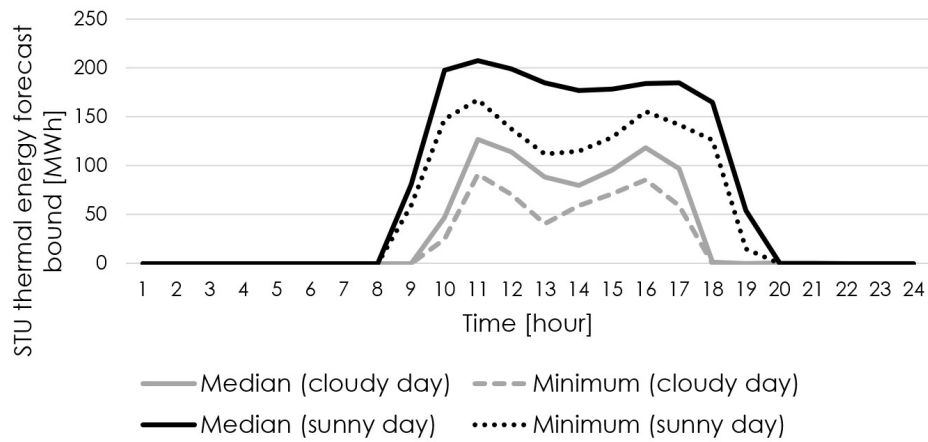


Figure A-3 STU energy forecast bounds

Wind Generation in the DAM

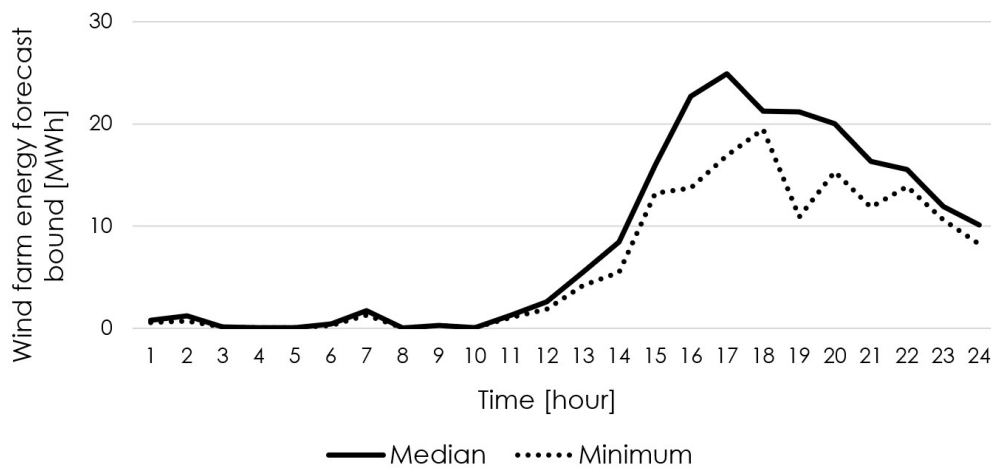


Figure A-4 Wind farm energy forecast bounds

Demand Profiles in DAM

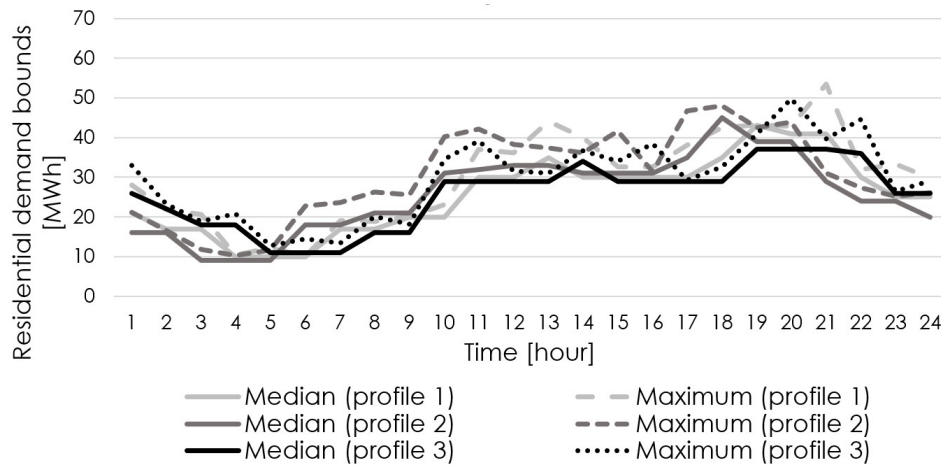


Figure A-5 Residential demand energy forecast bounds

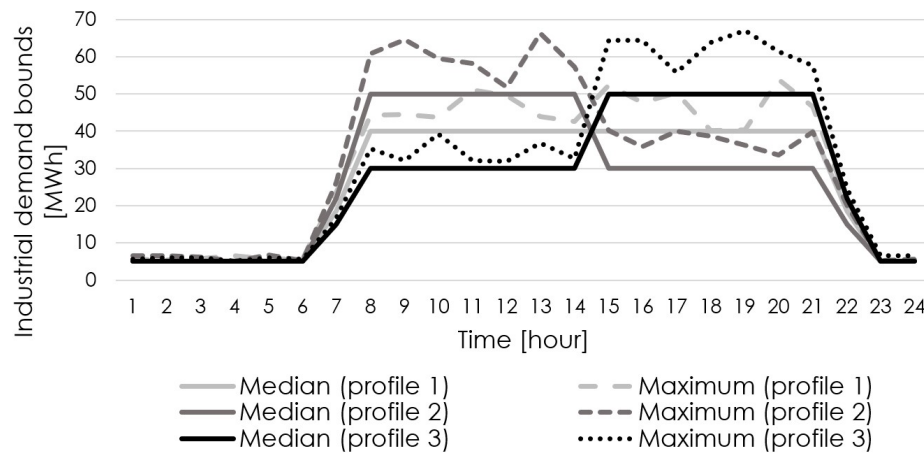


Figure A-6 Industrial demand energy forecast bounds

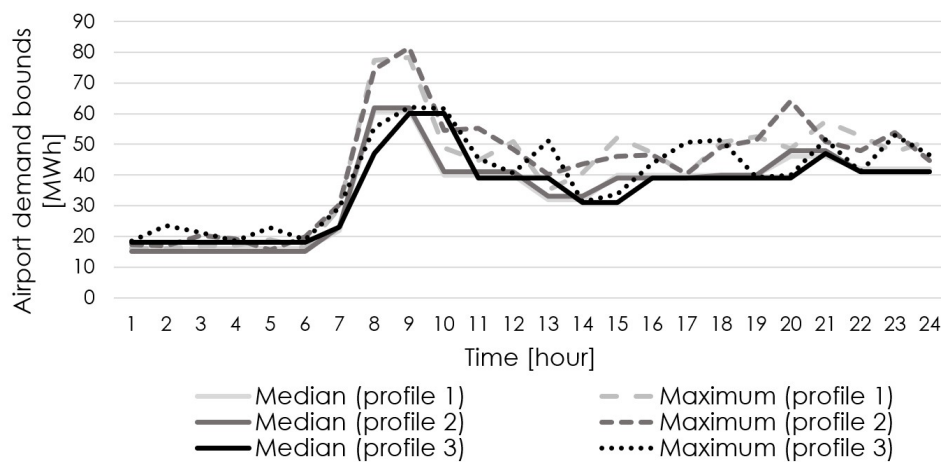


Figure A-7 Airport demand energy forecast bounds

Energy and Secondary Reserve Market Prices

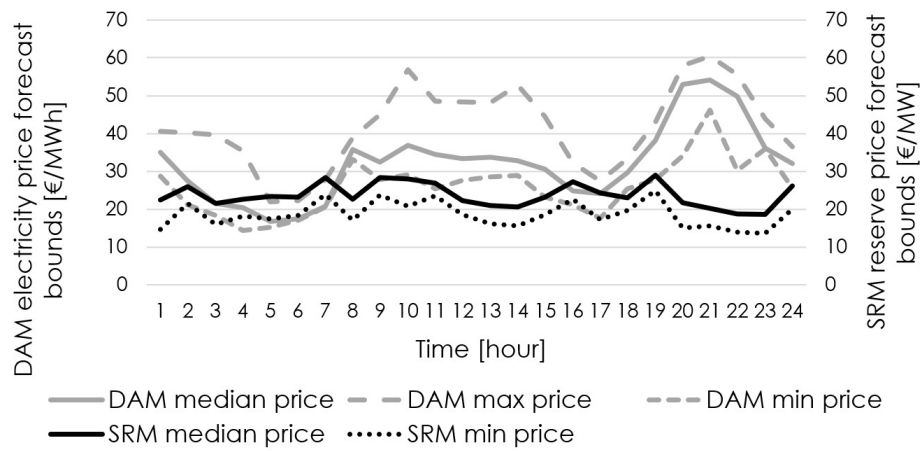


Figure A-8 DAM electricity price and SRM reserve price forecast bounds

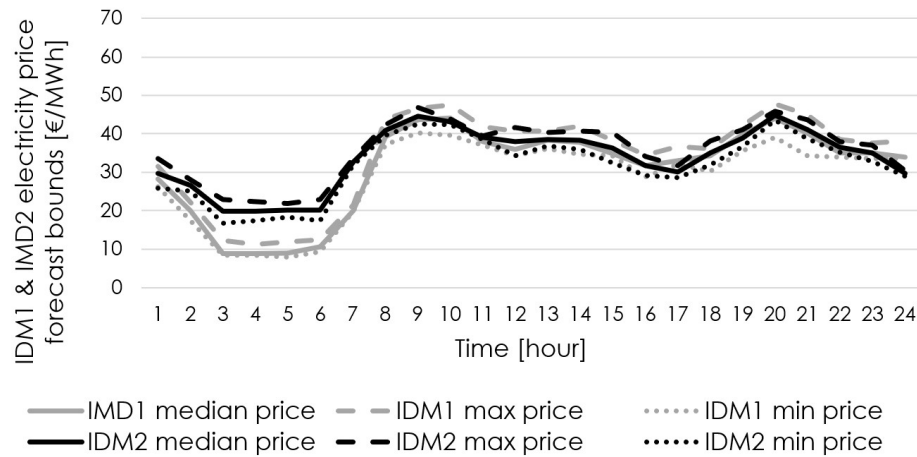


Figure A-9 IDM1 & IDM2 electricity price forecast bounds

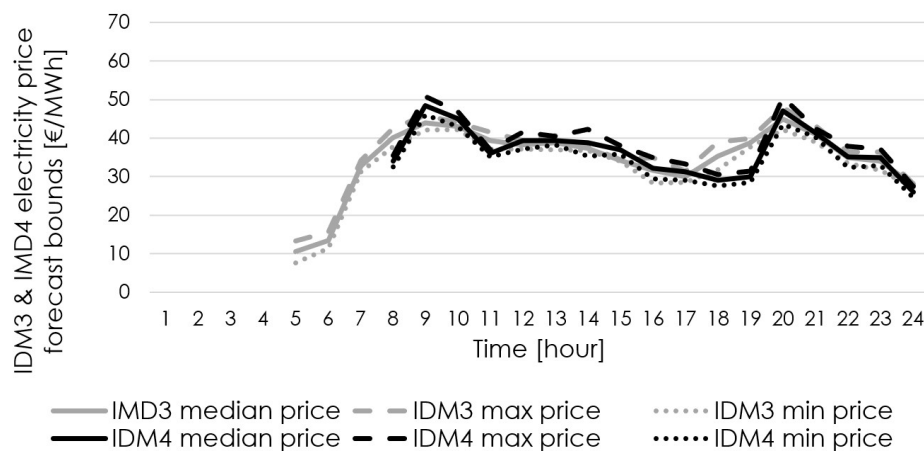


Figure A-10 IDM3 & IDM4 electricity price forecast bounds

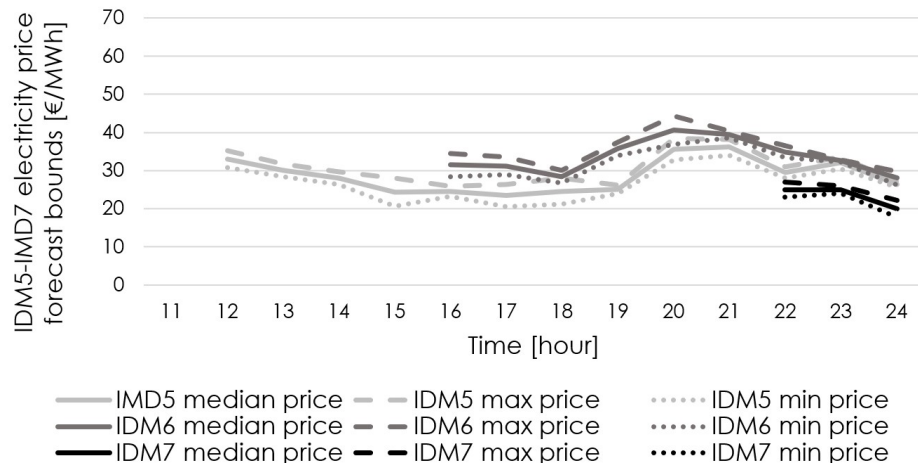


Figure A-11 IDM5-IDM7 electricity price forecast bounds

B Chapter 4' Complementary Simulation Results

This Appendix collects the detailed simulation results and their discussions that were omitted from Chapter 3. Such results have been divided according to the Case Study they refer to, namely Case 1 (Appendix B.1), and Cases 4-5 (Appendix B.2).

B.1 Case Study 1

Figure B-1 collects the results of the detailed productions of each of the generating unit in the DVPP, similar to that shown in Fig. 4-12 for the sunny day in the Spanish system.

For the optimistic case, the solar PVs and STU production is decreased compared to production of these units in the sunny day in Fig. 4-12a) and the effect is more significant after hour 13. The STU produces energy in hours 10-11, and 19-23 to help the DVPP to supply the first and second peaks of demands.

In the balanced case, the production of DVPP units has more fluctuation compared to optimistic case. The maximum production of DVPP happens in hour 10 in which most of the units except for wind farm has production.

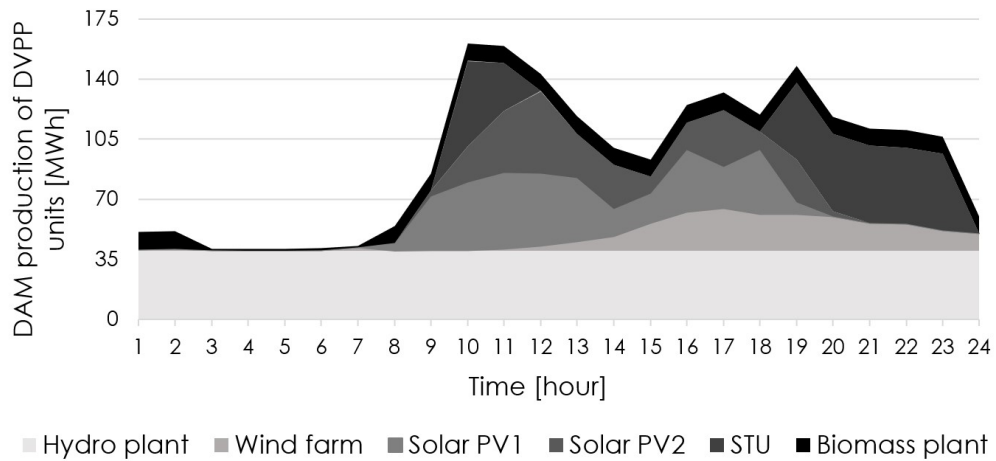
We can also observe, for the pessimistic strategy, that the STU only produces energy in the last hours 20-22 as the energy uncertainty is considered in more hours compared to balanced case.

Figure B-2 shows the charging/discharging powers, and the SoC of the STU in the Spanish DVPP for a cloudy day, similarly to what is shown in Fig. 4-16 for the sunny day.

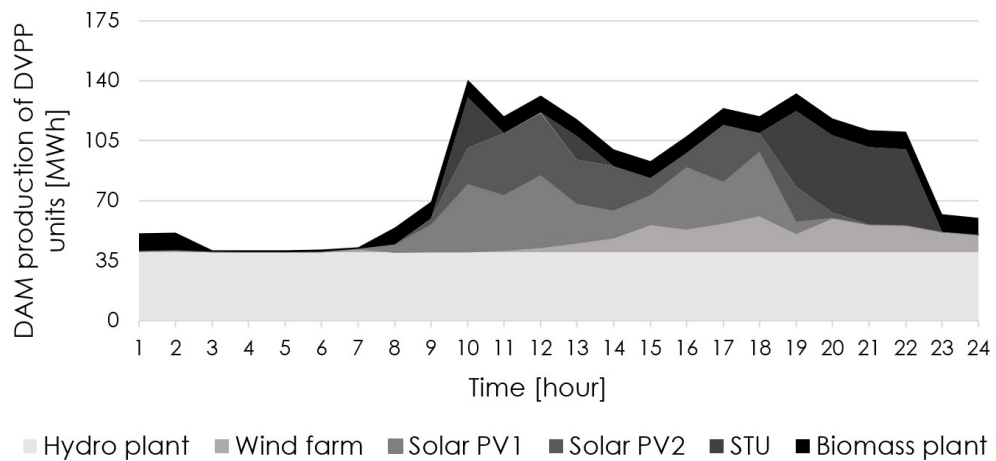
For the optimistic case, the STU thermal storage discharges in hours 10 and 18-23. Comparing to sunny day, in which the STU thermal storage starts discharging in hour 8 to supply the early peak demand, the situation is different in the cloudy day. In the cloudy day, as the thermal production of solar field is negligible, and the STU thermal storage SoC is low, the STU cannot start producing energy until hour 10 that solar field thermal production is increased.

For the balanced case, the trend of SoC of STU thermal storage is similar to the optimistic case. However, the charging/discharging power of thermal storage is reduced in hours 10, 12, 13, 16, and 26 compared to optimistic case due to considering uncertainty.

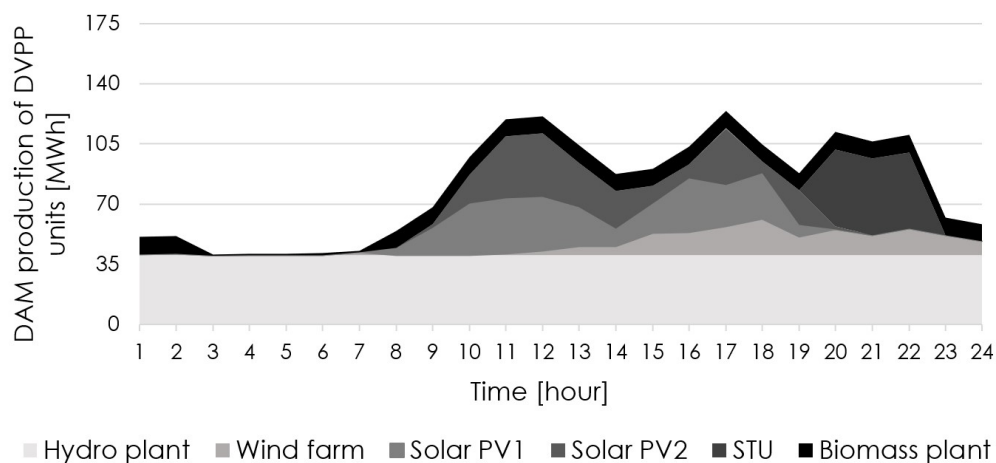
For the pessimistic case, the STU thermal storage due to lack of solar field thermal production even changes its state to charging at hour 10. In this case, the SoC in most of the time periods is lower than 40%. Besides, the charging/discharging power of thermal storage is reduced more than optimistic and balanced cases. Therefore, the STU thermal storage only discharges between hours 20-22.



a) Optimistic strategy

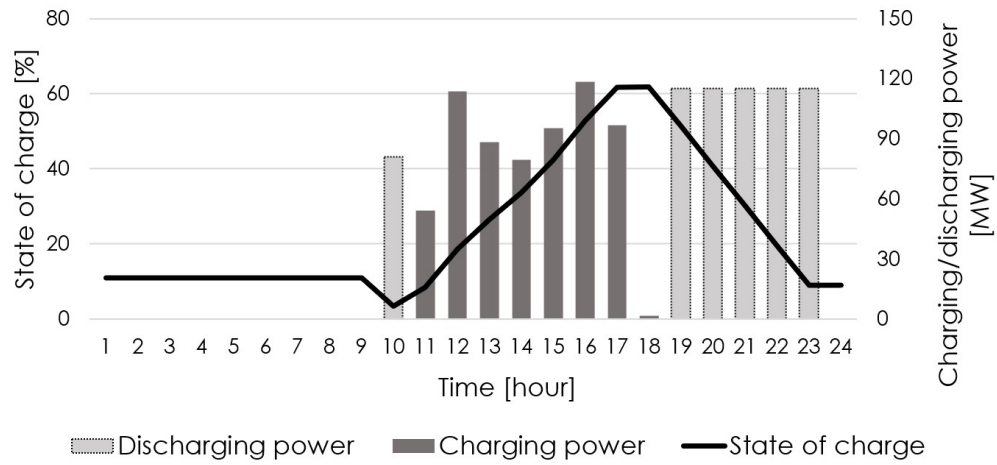


b) Balanced strategy

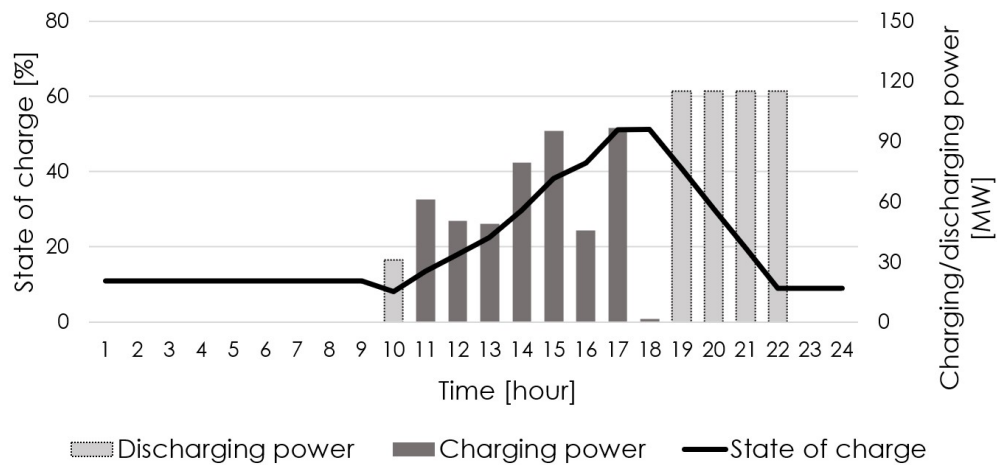


c) Pessimistic strategy

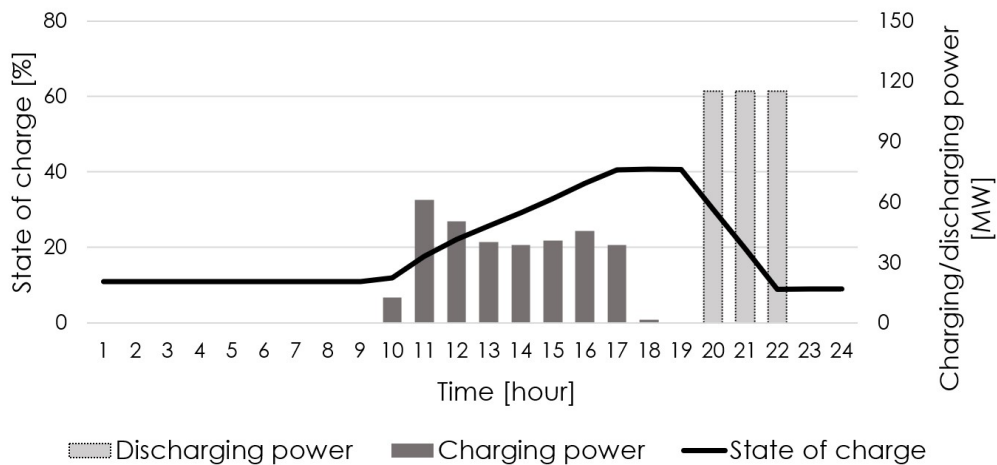
Figure B-1 DAM production of DVPP generating units for different market participation strategies for a cloudy day in the Spanish system



a) Optimistic strategy



b) Balanced strategy



c) Pessimistic strategy

Figure B-2 SoC and charging/discharging power of STU thermal storage for different DAM market participation strategies for a cloudy day in the Spanish system

B.2 Case Studies 4 and 5

The results included in this Section aim to complement and support the discussions and conclusions presented in Section 4.3.5. Sections B.2.1-B.2.3 provides the economic results of the three scenarios defined for Case Study 4 (favorable weather conditions), whereas Sections B.2.4-B.2.6 correspond to Case Study 5 (adverse weather conditions).

B.2.1 Scenario 4.1: No Aggregation Allowed

In Scenario 4.1, it is assumed that each unit separately participates in different electricity markets. This scenario is considered as the base case for further simulations.

Table B-1 shows the profit and different costs related to hydro plant in the DAM+SRM snapshot for optimistic, balanced, and pessimistic cases. The profit and costs for hydro plant unit is calculated by the assumption that hydro plant submit both energy and reserve offers in the DAM+SRM snapshot. By considering the uncertainty, the total profit that hydro plant can obtain in the balanced and pessimistic cases is reduced by 44% and 86% compared to optimistic case, respectively. These reductions are mainly due to considering more volatility in electricity and reserve prices in the balanced and pessimistic cases which in turn leads to lower profit. The biggest part of DVPP revenue comes from DAM. The proportion of DAM revenue of DVPP compared to its total revenue for optimistic, balanced, and pessimistic cases is 77%, 75%, and 58%, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 18%, 28%, and 52%, respectively.

Table B-1 Hydro plant profit and costs in the DAM+SRM snapshot for optimistic, balanced, and pessimistic cases

Robustness strategy	Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	DAM	25634	31754	6120	0
	SRM	9250	9250	0	0
	Total	34884	41004	6120	0
Balanced	DAM	11483	27636	5447	10706
	SRM	8134	9250	0	1115
	Total	19617	36886	5447	11821
Pessimistic	DAM	-1919	12439	2481	11876
	SRM	6695	9151	0	2456
	Total	4776	21590	2481	14332

Table B-2 shows the profit and different costs related to wind farm1 in the DAM+SRM for optimistic, balanced, and pessimistic cases. Table B-3 shows the same information for wind farm2.

The total profit of wind farm1 for optimistic, balanced, and pessimistic cases are 61335€, 27144€, and 8372€, respectively. This is understandable that DVPP sells less energy and have higher robust cost in more severe robustness strategies consequently the total profit is lower than optimistic case. The revenue that comes from DAM compared to the total revenue for optimistic, balanced, and pessimistic cases is 77%, 68%, and 49%, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 24%, 35%, and 51%, respectively.

The total profit of wind farm2 for balanced and pessimistic cases compared to optimistic case is reduced by 53% and 85%, respectively. The revenue that comes from DAM compared to the total revenue for optimistic, balanced, and pessimistic cases is 78%, 71%, and 44%, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 24%, 39%, and 37%, respectively.

Table B-2 Wind farm1 profit and costs in different electricity markets

Robustness strategy	Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	DAM	44254	58833	14579	0
	SRM	17081	17081	0	0
	Total	61335	75914	14579	0
Balanced	DAM	12490	35887	9485	13912
	SRM	14654	17081	0	2427
	Total	27144	52968	9485	16339
Pessimistic	DAM	-3531	15998	4255	15274
	SRM	11903	16452	0	4548
	Total	8372	32449	4255	19822

Table B-3 Wind farm2 profit and costs in different electricity markets

Robustness strategy	Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	DAM	29472	39438	9967	0
	SRM	11276	11276	0	0
	Total	40747	50714	9967	0
Balanced	DAM	9445	28527	7570	11511
	SRM	9820	11276	0	1455
	Total	19265	39802	7570	12966
Pessimistic	DAM	-1823	8259	2197	7886
	SRM	7738	10553	0	2814
	Total	5915	18812	2197	10700

Table B-4 shows the profit and different costs related to Solar PV in the DAM+SRM for optimistic, balanced, and pessimistic cases.

The total profit of Solar PV for optimistic, balanced, and pessimistic cases are 12989, 2445, and 75 €, respectively. The revenue that comes from DAM compared to the total revenue for optimistic, balanced, and pessimistic cases is 79%, 49%, and 28%, respectively. The proportion of total operation cost to total profit for the above cases are 11%, 12%, and 45%, respectively.

Table B-4 Solar PV profit and costs in different electricity markets for optimistic case

Robustness strategy	Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	DAM	10016	11443	1427	0
	SRM	2974	2974	0	0
	Total	12989	14417	1427	0
Balanced	DAM	370	2419	302	1747
	SRM	2075	2525	0	450
	Total	2445	4944	302	2197
Pessimistic	DAM	-321	264	34	551
	SRM	396	676	0	280
	Total	75	941	34	832

B.2.2 Scenario 4.2: Only ND-RESs Allowed

In this section, it is assumed that only ND-RESs are aggregated and can participate in the energy and reserve markets as a DVPP. Therefore, the DVPP in this section includes wind farm1, wind farm1, and solar of Fig. 4-2. The hydro plant participates in the market separately.

Table B-5 shows the profit and different costs related to DVPP in the DAM+SRM for optimistic, balanced, and pessimistic cases.

The total profit of DVPP for optimistic, balanced, and pessimistic cases are 115323 €, 52705 €, and 17291 €, respectively. The revenue that comes from DAM compared to the total revenue for optimistic, balanced, and pessimistic cases is 78%, 69%, and 45%, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 22%, 32%, and 34%, respectively.

Table B-6 compares the total profit and costs of scenario 4.1 (no aggregation is allowed) and scenario 4.2 (only ND-RESs aggregation is allowed) for optimistic, balanced, and pessimistic cases.

The proposed DVPP solution (scenario 4.2) can obtain 0.2%, 5.6%, and 15.3% higher profit compared to scenario 4.1 for optimistic, balanced, and pessimistic cases, respectively. Therefore, the DVPP solution is better than the solution that each unit

separately participates in the market especially for balanced and pessimistic cases. This is due to the fact that DVPP units can better cover each others uncertainty when they participate in the market as a single entity. A same result can be obtained by comparing the robust cost of DVPP solution to scenario 4.1. In scenario 4.1, the proportion of robust cost to total profit for balanced and pessimistic cases are 63% and 239%, respectively. In scenario 4.2, these proportions are reduced to 58% and 207%, respectively. Therefore the DVPP has higher impact than scenario 4.1 on alleviating both energy and price uncertainties.

Table B-5 ND-RESs profit and costs in different electricity markets for optimistic, balanced, and pessimistic cases

Robustness strategy	Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	DAM	83993	109714	25721	0
	SRM	31330	31330	0	0
	Total	115323	141044	25721	0
Balanced	DAM	25597	68592	16908	26087
	SRM	27108	31330	0	4222
	Total	52705	99922	16908	30309
Pessimistic	DAM	-4834	24449	5940	23343
	SRM	22135	30042	0	7917
	Total	17291	54491	5940	31261

Table B-6 Comparison between total profit and costs of Scenario 4.1 and 4.2 for optimistic, balanced, and pessimistic cases

Robustness strategy	Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	4.1	149955	182048	32093	0
	4.2	150207	182048	31841	0
Balanced	4.1	68471	134600	22804	43323
	4.2	72322	136808	22355	42130
Pessimistic	4.1	19138	73792	8967	45686
	4.2	22067	76081	8421	45593

B.2.3 Scenario 4.3: D-RESs and ND-RESs Allowed

In this section it is assumed that D-RESs and ND-RESs are aggregated and can participate in different energy and reserve markets as a DVPP. Therefore, the DVPP in this section includes hydro plant, wind farm1, wind farm2, and solar PV of Fig. 4-2.

Table B-7 shows the profit and different costs related to DVPP in the DAM+SRM for optimistic, balanced, and pessimistic cases.

The total profit of DVPP for optimistic, balanced, and pessimistic cases are 150567 €, 72941 €, and 23804 €, respectively. The revenue that comes from DAM compared to the total revenue for optimistic, balanced, and pessimistic cases is 78%, 70%, and 43%, respectively. The proportion of total operation cost to total profit for optimistic, balanced, and pessimistic cases are 21%, 30%, and 26%, respectively.

Table B-7 D-REs and ND-REs profit and costs in different electricity markets for optimistic, balanced, and pessimistic cases

Robustness strategy	Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	DAM	109987	141467	31481	0
	SRM	40580	40580	0	0
	Total	150567	182048	31481	0
Balanced	DAM	37677	95509	21604	36228
	SRM	35264	40580	0	5317
	Total	72941	136089	21604	41545
Pessimistic	DAM	-4850	29407	6179	28078
	SRM	28654	38948	0	10296
	Total	23804	68355	6179	38372

Table B-8 compares the total profit and costs of scenario 4.1 (no aggregation is allowed) and scenario 4.3 (D-REs and ND-REs aggregation is allowed) for optimistic, balanced, and pessimistic cases.

The proposed DVPP solution (scenario 4.3) can obtain 0.4%, 6.5%, and 24.4% higher profit compared to scenario 4.1 for optimistic, balanced, and pessimistic cases, respectively. Therefore, the DVPP solution is better than the solution that each unit separately participates in the market especially for balanced and pessimistic cases. This is due to the fact that DVPP units can better cover each others uncertainty when they participate in the market as a single entity. A same result can be obtained by comparing the robust cost of DVPP solution to scenario 4.1. In scenario 4.1, the proportion of robust cost to total profit for balanced and pessimistic cases are 64% and 218%, respectively. In scenario 4.3, these proportions are reduced to 57% and 161%, respectively. Therefore the DVPP has higher impact than scenario 4.1 on alleviating both energy and price uncertainties.

B.2.4 Scenario 5.1: No Aggregation Allowed

In Scenario 5.1, it is assumed that each unit separately participates in the energy and reserve markets. This scenario is considered as the base case for further simulations.

Table B-9 shows the profit and different costs related to wind farm1 in the DAM+SRM in non-windy day for balanced case. Table B-10 shows the same information for wind farm2.

Table B-8 Comparison between total profit and costs of Scenarios 4.1 and 4.3 for optimistic, balanced, and pessimistic cases

Robustness strategy	Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
Optimistic	4.1	149955	182048	32093	0
	4.3	150567	182048	31481	0
Balanced	4.1	68471	134600	22804	43323
	4.3	72941	136089	21604	41545
Pessimistic	4.1	19138	73792	8967	45686
	4.3	23804	68355	6179	38372

The total profit of wind farm1 for balanced case is 7616 €. The total profit of wind farm1 for non-windy day compared to windy day is reduced by 72%. The revenue that comes from DAM compared to the total revenue for balanced cases is 36%. The proportion of total operation cost and robust cost to total profit is 25% and 139%, respectively. The wind farm operation cost in non-windy day compared to windy day is reduced since the wind farm has less production.

The total profit of wind farm2 for balanced case is 11935 €. The total profit of wind farm2 for non-windy day compared to windy day is reduced by 38%. The revenue that comes from DAM compared to the total revenue for balanced cases is 72%. The proportion of total operation cost and robust cost to total profit is 37% and 59%, respectively.

Table B-9 Wind farm1 profit and costs in different electricity markets in non-windy day for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	-1596	7232	1923	6905
SRM	9212	12876	0	3663
Total	7616	20107	1923	10568

Table B-10 Wind farm2 profit and costs in different electricity markets in non-windy day for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	6194	16901	4468	6240
SRM	5741	6582	0	841
Total	11935	23483	4468	7081

B.2.5 Scenario 5.2: Only ND-RESs Allowed

In this section, it is assumed that only ND-RESs are aggregated and can participate in the energy and reserve markets as a DVPP for a non-windy day. Therefore, the DVPP in this section includes wind farm1, wind farm2, and solar PV of Fig. 4-2. The hydro plant participates in the market separately.

Table B-11 shows the profit and different costs related to DVPP in the DAM+SRM and in the non-windy day for balanced case.

The total profit of DVPP for balanced case is 39786 €. The revenue that comes from DAM compared to the total revenue is 51%. The proportion of total operation cost and robust cost to total profit is 35% and 68%, respectively.

Table B-11 ND-RESs profit and costs in different electricity markets in non-windy day for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	20372	57978	13798	23808
SRM	19414	22602	0	3187
Total	39786	80580	13798	26996

Table B-12 compares the total profit and costs of scenario 5.1 (no aggregation is allowed) and scenario 5.2 (only ND-RESs aggregation is allowed) in non-windy day for balanced case.

The proposed DVPP solution (scenario 5.2) can obtain 43% higher profit compared to scenario 5.1 for balanced case. This extra benefit is higher than the extra profit for a same comparison for windy day (between scenario 4.1 and 4.2). The reason is that for non-windy day the forecast is less accurate, therefore the aggregation can be more beneficial. The proportion of robust cost to total profit for scenario 5.1 and 5.2 are 76% and 65%, respectively. Therefore, aggregation of ND-RESs in scenario 5.2 can alleviate the uncertain parameters and brings more benefit for DVPP.

Table B-12 Comparison between total profit and costs of scenario 5.1 (no aggregation is allowed) and scenario 5.2 (only ND-RESs aggregation is allowed) in non-windy day for balanced case

Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
5.1	41613	85420	12140	31667
5.2	59403	117466	19245	38817

B.2.6 Scenario 5.3: D-RESs and ND-RESs Allowed

In this section it is assumed that D-RESs and ND-RESs are aggregated and can participate in the energy and reserve markets as a DVPP for a non-windy day. Therefore, the DVPP in this section includes hydro plant, wind farm1, wind farm2, and solar PV of Fig. 4-2.

Table B-13 shows the profit and different costs related to DVPP in the DAM+SRM in non-windy day for balanced case.

The total profit of DVPP for balanced case is 39786 €. The revenue that comes from DAM compared to the total revenue is 54%. The proportion of total operation cost and robust cost to total profit is 32% and 67%, respectively.

Table B-13 D-RESs and ND-RESs profit and costs in different electricity markets in non-windy day for balanced case

Electricity market	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
DAM	32973	88866	19434	36459
SRM	27575	31852	0	4277
Total	60548	120718	19434	40736

Table B-14 compares the total profit and costs of scenario 5.1 (no aggregation is allowed) and scenario 5.3 (D-RESs and ND-RESs aggregation is allowed) in non-windy day for balanced case.

The proposed DVPP solution (scenario 5.3) can obtain 46% higher profit compared to scenario 5.1 for balanced case. The proportion of robust cost to total profit for scenario 5.1 and 5.3 are 76% and 67%, respectively. Therefore, the results show the superiority of aggregation of D-RESs and ND-RESs compared to no coordination solution in terms of profit and robust cost.

Table B-14 Comparison between total profit and costs of scenario 5.1 (no aggregation is allowed) and scenario 5.3 (D-RESs and ND-RESs aggregation is allowed) in non-windy day for balanced case

Scenario	Profit [€]	Incomes [€]	Operation cost [€]	Robust cost [€]
5.1	41613	85420	12140	31667
5.3	60548	120718	19434	40736