D 5.1 Integration of standardized flexibility requirements and multi-market commercialization of flexibility in a virtual power plant

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Executive Summary

The energy landscape is evolving rapidly, requiring adaptable and flexible energy solutions. In response to this need, Virtual Power Plants (VPPs) have emerged as a sophisticated method to integrate various distributed energy resources (DERs) such as solar panels, wind turbines, battery storage systems, and flexible loads. By managing these resources as a single entity, VPPs optimize their combined output, demonstrating significant potential in enhancing energy efficiency and market performance.

The primary goal of implementing VPPs is to showcase the feasibility and benefits of multi-market commercialization of flexibility. This involves the seamless integration of DERs and the establishment of standardized flexibility requirements to optimize interactions and performance across different energy markets. In this context, a VPP functions as a single power plant, executing tasks like monitoring, forecasting, optimizing, and trading energy. The VPP in this study is particularly designed with a bidding algorithm to participate in various markets, including day-ahead, balancing, and redispatch markets, aiming to optimize profits and enhance flexibility by leveraging generation forecasts and market conditions.

The study outlines assumptions regarding technical, regulatory, and market conditions. These include market rules, physical framework conditions, price forecasts, and activation probabilities.

The VPP’s bidding algorithm is implemented using a mixed integer linear program, modeling market behavior and optimizing bid volumes for different markets. Data integration involves normalizing and scaling market data, considering seasonal and daily variations, and using representative weeks for each season to capture a broad range of market scenarios.

This deliverable sets the groundwork for further exploration within the DigIPlat project, aiming to enhance the understanding and application of VPPs in the dynamic energy market landscape.

Kurzfassung

Die heutige Energielandschaft entwickelt sich rasch weiter und erfordert anpassungsfähige und flexible Energielösungen. Als Antwort auf diesen Bedarf haben sich Virtuelle Kraftwerke (VPPs) als Methode zur Integration verschiedener verteilter Energiequellen (DERs) wie Solaranlagen, Windkraftanlagen, Batteriespeichersysteme und flexible Lasten etabliert. Durch die Verwaltung dieser Ressourcen als eine Einheit optimieren VPPs deren kombinierten Output und zeigen erhebliches Potenzial zur Steigerung der Energieeffizienz und der Marktleistung.

Das Hauptziel der Implementierung von VPPs besteht darin, die Machbarkeit und Vorteile der Multimarkt-Kommerzialisierung von Flexibilität aufzuzeigen. Dies beinhaltet die nahtlose Integration von DERs und die Etablierung standardisierter Flexibilitätsanforderungen, um die Interaktionen und Leistung über verschiedene Energiemärkte hinweg zu optimieren. In diesem Zusammenhang fungiert ein VPP als ein einzelnes Kraftwerk, das Aufgaben wie Überwachung, Prognose, Optimierung und Handel mit Energie ausführt. Das in dieser Studie untersuchte VPP ist mit einem speziell Bietalgorithmus ausgestattet, um an verschiedenen Märkten, einschließlich des Day-Ahead-, Regelreserve- und Redispatch-Marktes, teilzunehmen und dabei die Gewinne zu maximieren und die Flexibilität zu erhöhen, indem es Erzeugungsprognosen und Marktbedingungen nutzt.

Dieses Deliverable skizziert Annahmen bezüglich technischer, regulatorischer und marktbezogener Bedingungen. Dazu gehören Marktregeln, physische Rahmenbedingungen, Preisprognosen und Aktivierungswahrscheinlichkeiten.

Der Bietalgorithmus des VPP wird mittels eines gemischt-ganzzahligen linearen Programms implementiert, das Marktverhalten modelliert und Gebotsvolumina für verschiedene Märkte optimiert. Die Datenintegration umfasst die Normalisierung und Skalierung von Marktdaten unter Berücksichtigung saisonaler und täglicher Schwankungen und die Verwendung repräsentativer Wochen für jede Jahreszeit, um ein breites Spektrum von Marktszenarien abzudecken.

Dieses Dokument bildet die Grundlage für weitere Untersuchungen im Rahmen des DigIPlat-Projekts und zielt darauf ab, das Verständnis und die Anwendung von VPPs in der dynamischen Energielandschaft zu verbessern.

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List of abbreviations

ABM	*agent-based model*
BC	*balancing capacity*
BE	*balancing energy*
DA	*day-ahead*
DERs	*distributed energy resources*
DRL	*deep reinforcement learning*
GCT	*o Gate closure time*
MILP	*mixed integer linear program*
RD	*redispatch*
TSO	*Transmission System Operator*
UC 2	*Use Case 2*
VPP	*Virtual Power Plant*

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1 Introduction

In today's changing energy markets, adaptability is crucial. New flexibility platforms are making a big impact by allowing easy commercialization of flexible resources in various energy markets. Central to this change is efficient coordination and optimization, where market interactions and standardized flexibility requirements come together to foster innovation and resilience.

This deliverable aims to provide a comprehensive understanding of multi-market commercialization, focusing on the exemplary simulation of a Virtual Power Plant (VPP) as a tool for testing and analysis. Here, our primary objective is to set the stage and establish the groundwork for subsequent simulations and analyses that will be done as part of the DigIPlat project. Within our work, we specifically focus on Use-Case 2 (UC 2), developed in [1], delving into multi-market commercialization, by exploring how the integration of a VPP facilitates the flexible trading of resources across various energy markets. Central to our exploration is the integration of standardized requirements within the VPP optimization framework, facilitating a comprehensive evaluation of its multi-market behaviour from the perspective of market participants. Specifically, we illuminate the interplay between market dynamics and flexibility provision across four distinct markets: the day-ahead, redispatch, balancing capacity, and balancing energy markets.

In the course of this deliverable, we focus solely on how the VPP is integrated and how UC 2 is implemented. We establish the basis for later work that will be conducted in the course of the DigIPlat project, focusing on setting the scene for the technical implementation of the Use-Case and outlining the underpinning assumptions to our modelling efforts. Through this deliverable, we aim to provide a comprehensive overview of our methodology, motivations, and assumptions, setting the stage for the deeper exploration that lies ahead in the DigIPlat project.

2 Motivation and overview of Virtual Power Plant

Generally speaking, a VPP is an aggregation system that integrates various distributed energy resources (DERs) such as solar panels, wind turbines, battery storage systems, and flexible loads, to create an optimized network that can be managed and operated as if it were a single power plant. Depending on the defined scenario, VPPs can be used for different tasks, including monitoring, forecasting, optimizing, and trading their power.

In our special case, the VPP offers a bidding algorithm designed for participation in various energy markets, encompassing aggregation, scheduling, and energy management. The algorithm is based on a mixed integer linear program formulation.

In addition to providing redispatch services, the VPP actively engages in multiple markets, including day-ahead (DA) and balancing markets, aiming to optimize cumulative profits and enhance flexibility based on its generation forecast.

The framework models the bidding behaviour, accounting for generation forecasts and considering inputs such as activation and awarding probabilities for balancing energy (BE) and redispatch (RD) as well as expected prices across different markets.

Market rules as well as physical framework conditions are translated into mathematical constraints.

The results consist of volumes of bids to be placed at the different markets. The effectiveness of the bidding strategy is heavily dependent on realistic inputs for price forecasts, activation or awarding probabilities, and production forecasts.

In general, the main added value of this model framework is allowing multi-market commercialization of flexible resources. Based on standardized requirements, we simulate an example VPP to test multi-market commercialization of flexibility from the point of view of the market participants.

3 Multi-market commercialization of flexibility

In the course of the DigIPlat project, three different flexibility Use-Cases have been defined, with one of them focusing on optimal procurement of balancing energy of distribution grid connected assets, and the other two illuminating the multi-market commercialization of flexibility products [1]. In this Deliverable, we focus on UC 2, analyzing how flexibility procurement could be streamlined across markets to minimize congestion management costs, particularly those associated with redispatch. Specifically, it aims to evaluate the use?of balancing capacity bids directly for redispatch measures. This is done by creating a common tool that facilitates the opportunity to re-offer unaccepted bids (or only partially accepted bids) in other (subsequent) markets. We call this approach “bid forwarding”[2].

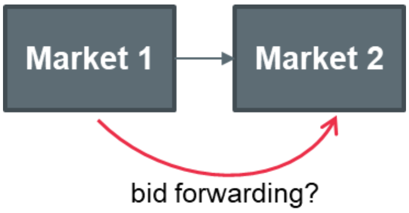

Figure 1 Illustration of the concept of bid forwarding

This approach offers dual benefits: first, it allows sellers to trade their goods across different markets via bid forwarding, and second, it reduces the incentive for engaging in gaming strategies. The latter objective is expected to be achieved by incentivizing bidding decisions before the day-ahead market clearing, thereby reducing the ability to predict congestion occurrences in the grid and potentially enhancing overall market liquidity and competitiveness.

For a successful examination of Use-Case 2 we implement the DA market, RD market, balancing capacity (BC) and BE market. By analyzing the DA and RD market, we account for the potential emergence of inc-dec gaming due to market-based redispatch remuneration.

Generally, 'bid forwarding' is implemented within the model by relaxing the agents' constraint of reserving accepted capacity from the BC market to also use it for bids on the RD market. This, in turn, provides the Transmission System Operator (TSO) with greater flexibility in activating the appropriate assets.

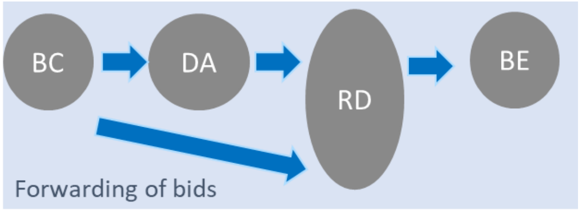

Figure 2 Conceptual depiction of UC 2

3.1 Implementation

Anticipating benefits on both fronts—enhancing prosumer margins through increased activation probabilities and reducing consumer costs by mitigating gaming-related expenses—we approach our analysis from two distinct perspectives:

1. Employing a VPP that mimics a flexibility provider equipped with photovoltaic panels and combined battery storage, we optimize volume allocation across markets to evaluate the effects of facilitating bidding flexibilities.
2. Utilizing deep reinforcement learning (DRL) agents as "attackers" to exploit potential weaknesses in the considered market design.

For both tasks, we develop an agent-based model (ABM) that mirrors the four relevant markets in our study: the BE and BE market, the DA market, and a RD market. Additionally, we integrate the market model with a six-bus electricity network, as documented in the literature, to analyze the impact of gaming in market-based redispatch. This model configuration enables us to address the intended use case objectives while ensuring model reliability by aligning it closely with real-world scenarios. Furthermore, basing this setup on scenarios from the literature aids in validation.

The VPP operates on a mixed integer linear program (MILP), integrating data from DRL to overcome the limitations inherent in conventional optimization methods (see Figure 3). More precisely, MILP relies on the integration of historical data to include clearing price predictions and activation probabilities. However, when assessing new market designs, the availability of relevant data is naturally sparse or nonexistent. DRL, by design, explores the environment in detail, allowing the derivation of missing data from pre-training generated datasets directly.

We first utilize DRL to generate insightful data, which we then integrate into the VPP for optimization. This approach is similar to Monte Carlo sampling, with the distinction that DRL applies gradient descent methods to exploit more efficient bidding behavior. Consequently, the resulting bids from the VPP comprise prices determined by the DRL agent combined with the volume bids from the VPP.

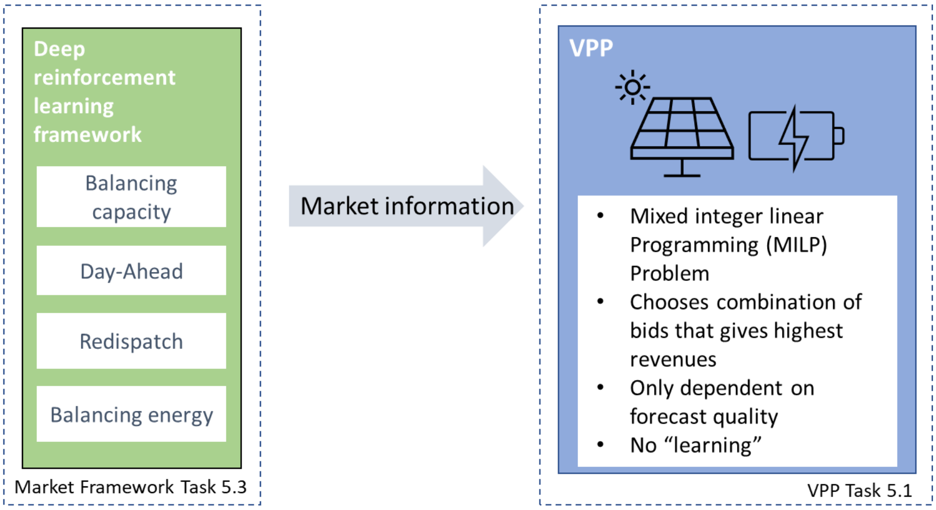

Figure 3 Overview of interaction between DRL and VPP

4 Assumptions

4.1 Technical and regulatory assumptions

It is required that the flexibility asset that provides a bid is prequalified for all markets the bid shall be forwarded to. The battery considers linearized standby losses as well as linearized charging and discharging losses. The PV is assumed to be continuously curtailable between 0 and the maximum current amount of production. The sizing of the battery and the photovoltaic plant will be chosen according to the concrete scenario. Results and concrete input numbers will be described in Deliverable 5.3.

4.2 Market assumptions

For simplification, we assume that all markets clear based on four consecutive hours, representing relevant demand fluctuations during a day, and considering four different weeks to reflect seasonal dependencies. Agents can place single bids per hour, with bids considered divisible. DRL agents determine both price and volume bids, while the VPP decides solely on volume bids. We consider only a 1-hour time resolution for all markets. This restriction is due to the requirement for DRL to have a discrete action vector size for possible bids. Note that while the number of possible bids is discrete, the bids themselves are selected from a continuous action space. As mentioned above, the final bids are a conjunction of DRL price bids and VPP based volume bids, therefore restricting also this time resolution for VPP.

The objective function of the VPP that is being minimized comprises as follows:

$$costs = \sum_t costs_{DA}(t) - profits_{FRR,C}(t) - profits_{FRR,E}(t) - profits_{redispatch}(t)$$

All constraints are formulated to ensure that full activation, whether in a positive or negative direction, can be achieved (assuming there are no forecast deviations).

Table 1 Explanation of variables I

$costs$	total costs (revenues if ≤ 0)	[€]
$costs_{DA}(t)$	costs (revenues if ≤ 0) from bids at the day ahead market	[€]
$profits_{FRR,C}(t)$	expected revenues from the balancing capacity (≥ 0)	[€]
$profits_{FRR,E}(t)$	expected revenues from the balancing energy (≥ 0)	[€]
$profits_{redispatch}(t)$	expected revenues from redispatch bids (≥ 0)	[€]

4.2.1 Spot market

Day-Ahead Market:

Remunerates energy bids based on pay-as-cleared. The VPP considers all amounts that have been traded in the balancing capacity market as constraints, to always ensure a potential activation of balancing energy. This reflects realistic agent behavior, as they are essentially contracted to ensure the availability of their promised goods upon acceptance for reserving their capacities in the balancing capacity market.

- Assumptions:
    - Gate closure time (GCT): 12:00 DA
    - 1h product
    - Pay-as-Cleared Market
- Frequency of optimization:
    - Once, day ahead
    - Accepted bids are considered as fixed in further optimization runs
- Input for VPP:
    - Expected clearing prices in hourly resolution
- Output:
    - Bid volumes in hourly resolution
- VPP profit function:
    - $costs_{DA}(t) = p_{DA}(t) * da_{Total}(t)$

Table 2 Explanation of variables II

$da_{TOTAL}(t)$	Bid volume at the day-ahead market	[kW]
$p_{DA}(t)$	Expected clearing price at the day-ahead market at timerstep t	$[\frac{€}{MWh}]$

4.2.2 Balancing market(s)

Balancing capacity market:

Negative and positive capacity are procured and remunerated based on pay-as-bid. Profits are calculated without considering marginal costs, those are considered only for energy transactions. This approach is based on the premise that no costs are incurred for withholding capacity, while sales on the day-ahead market are assumed to cover marginal costs.

- Assumptions:
    - GCT: 10:00 DA
    - 1h product[1]
    - Pay-as-bid market
- Frequency of optimization:
    - Once, day-ahead
    - Accepted bids are further considered as fixed in other optimization runs
- Input for VPP:
    - Expected prices in hourly resolution
    - Awarding probability (dependent on price)
- Output:
    - Bid volumes in hourly resolution
- VPP profit function:
    - $profits_{FRR,C}(t) = \ frr_{price_{pos}}^{capacity}(\,t) * frr_{pos}^{total}(t) + frr_{price_{neg}}^{capacity}(\,t) * frr_{neg}^{total}(t)$

Table 3 explanation of variables III

$profits_{FRR,C}(t)$	expected revenues from the balancing capacity (≥ 0)	[€]
$frr_{price_{dir}}^{capacity}(t)$	price for procurement of dir (pos or neg) capacity per timestep	[€/MWh]
$frr_{dir}^{total}(t)$	total amount of dir (pos or neg) bid volume per timestep and merit order position, > 0 for both directions	[kW]

4.2.3 Balancing energy market:

Energy bids are formed based on accepted capacities from the balancing capacity market and remunerated based on pay-as-cleared. We do not consider additional “free bids”; thus, agents potentially only decide on their price bids (i.e., this only affects DRL-agents, since VPP-agents do not decide on price bids).

Assumptions:

- GCT: t-25

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[1] As mentioned before, we standardized all markets to a 1-hour resolution due to the DRL's requirement for a discrete number of possible bids.

  - 1h product
  - Pay-as-cleared market
  - Plants bid their marginal prices
- Frequency of optimization:
  - Once, day of delivery
- Input for VPP:
  - Expected clearing price
  - Activation probability which is related to the bid price
- Output:
  - Bid volumes in hourly resolution
- VPP profit function:
  - $profits_{FRR,E}(t) = \; frr^{energy}_{price_{pos}}(\,t) * \; frr^{total}_{pos}(t) * \; frr^{prob}_{pos}(t) - \; frr^{energy}_{price_{neg}}(\,t) * frr^{total}_{neg}(t) * \; frr^{prob}_{neg}(t)$

Table 4 explanation of variables IV

$profits_{FRR,E}(t$	expected revenues from the balancing energy (≥ 0)	[€]
$frr^{energy}_{price_{dir}}(\,t)$	price for delivery of dir (pos or neg)energy per merit order position and timestep; price for neg balancing energy < 0	[€/MWh]
$frr^{total}_{dir}(t)$	total amount of dir (pos or neg) bid volume per timestep and merit order position, > 0 for both directions	[kW]
$frr^{prob}_{dir}(t)$	probability for dir (pos or neg) activation in timestep t and merit orde	[1]

4.2.4 Redispatch

Redispatch market:

Agents offer all available flexibilities, with accepted bids from the day-ahead market for downward regulation and leftover capacities for upward regulation. Sales are remunerated via pay-as-bid. Redispatch demand is determined by initially running a linear optimal power flow to identify congested lines and subsequently running the same optimization with fixed volumes from the day-ahead market and procured redispatch bids to resolve congestion.

- Assumptions:
  - GCT: 18:00 DA[2]
  - 1h product
  - Pay-as-bid market
- Frequency of optimization:
  - Once, at DA 18:00
- Input for VPP:
  - expected price, which is correlated with the activation probability
  - Activation probability
- Output:
  - Bid volumes in hourly resolution
- VPP profit function:

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[2] Assumption based on Austrain research project I4RD [3]

- $profits_{redispatch}(t) = -redispatch^{energy}_{price_{neg}}(t) \; * redispatch_{neg}(t) * redispatch^{prob}_{neg}(t) + redispatch^{energy}_{price_{pos}}(t) \; * redispatch_{pos}(t) * redispatch^{prob}_{pos}(t)$

$profits_{redispatch}(t)$	expected revenues from redispatch bids (≥ 0)	[€]
$redispatch_{dir}(t)$	the redispatch bid volume offered in dir ('pos'or 'neg')direct > 0 for both directions	[kW]
$redispatch^{energy}_{price_{dir}}(t)$	price for delivery of dir (pos or neg) energy per timestep price for neg redispatch	[€/MWh]
$redispatch^{prob}_{dir}(mol,t$	probability for dir (pos or neg) activation in timestep t ($\in [0,1]$)	[1]

4.3 Data

As mentioned before, we integrate the market model with a six-bus electricity network from the literature[4]. We divide this network into two connected zones with transmission limits between them, resulting in two different day-ahead prices. Only line capacities are considered, and demand is allocated to different buses.

Based on data from the six-bus network we scale open-source available data from the Austrian Grid Operator (APG)[5]:

- Day-ahead market: We standardize real day-ahead market data and scale it with data from the six-bus network.
- Balancing capacity and energy markets: We first normalize the data with that from the day-ahead market and then scale it with the scaled data from the day-ahead market.
- Redispatch market: We follow the same procedure as for the balancing market, intentionally sampling representative data to account for seasonal and daily fluctuation effects, creating different congestion scenarios for careful analysis.

As mentioned, we only consider four representative weeks for each season, along with four consecutive hours representing different parts of the day. Therefore, when standardizing and scaling our data, we first cluster them and then perform the described process within their respective clusters.

The used PV forecast relies on the overall solar availability in Austria. We integrate forecast errors by comparing the ENTSO-E weather forecasts with the observed solar availability [6].

Figure 4 visualizes the mode of operation under the assumptions of this chapter.

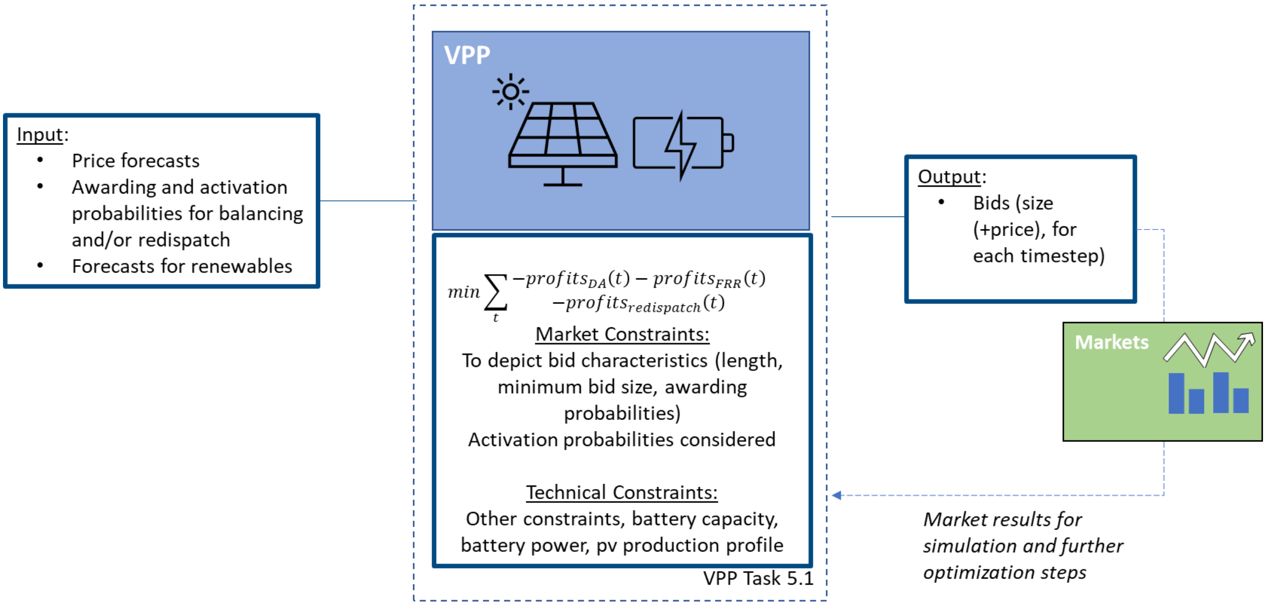

Figure 4 Overview of the VPP's mode of operation

4.4 Process description

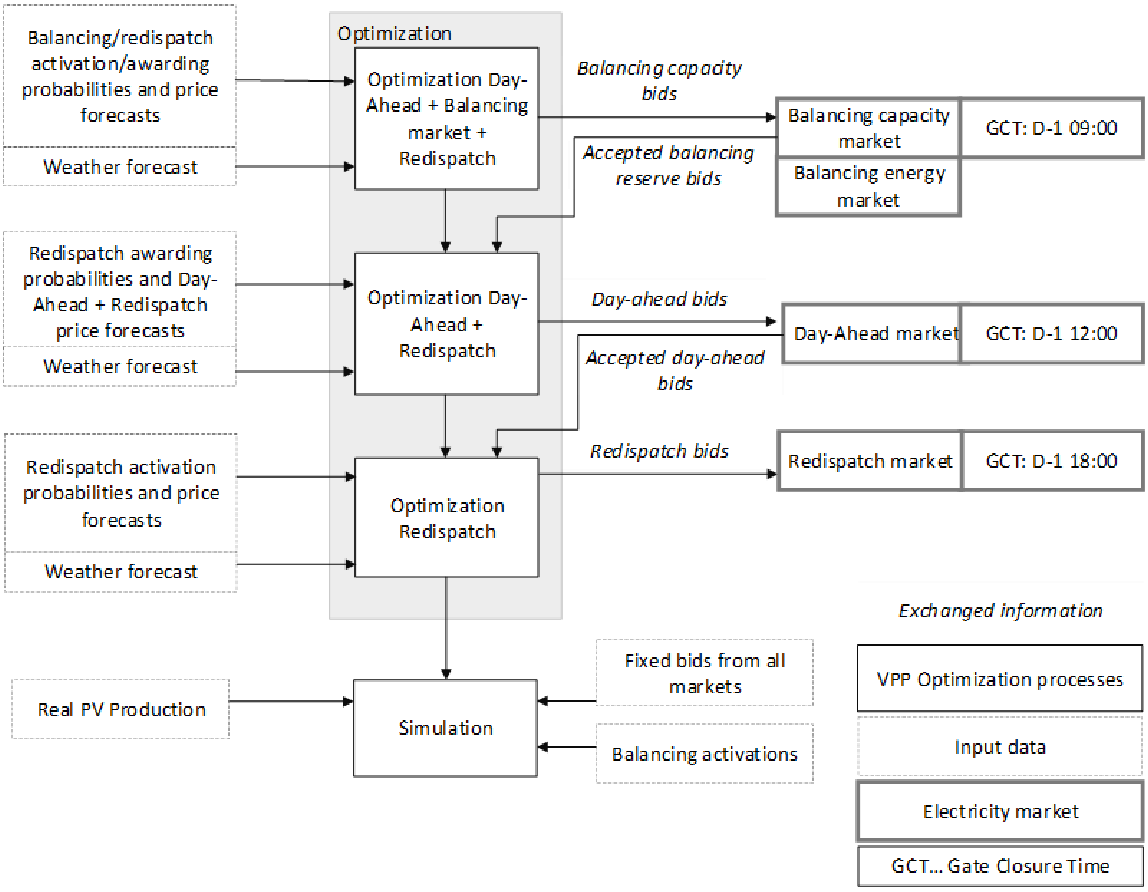

Figure 5 Process Description

5 Conclusion and next steps

In today's rapidly evolving energy landscape, the integration of standardized flexibility requirements and multi-market commercialization of flexibility is crucial. The convergence of market interactions with standardized flexibility requirements allows for a more cohesive and robust energy system. This alignment not only supports the efficient operation of VPPs but also contributes to the stability and sustainability of the broader energy market.

This deliverable has demonstrated how a comprehensive understanding of multi-market commercialization, focusing on the exemplary simulation of a Virtual Power Plant (VPP) as a tool for testing and analysis, can be achieved. Therefore, different aspects have been taken into account, considering technical and regulatory assumptions, different market assumptions, and forecast data.

All technical aspects leading up to the "data" section have been successfully implemented. This encompasses integrating a market environment, developing a framework for the described agents, including a grid scenario sourced from the literature, and evaluating the reliability of these methods. The subsequent steps entail conducting the actual investigation of UC 2, incorporating the predefined KPIs, within a simulation that utilizes the specified data. The results for the VPP optimization and a detailed description for the agent-based reinforcement learning model will be published in D5.3.

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