edgeFLEX

D5.2 Report on field trial of VPP operations optimisation in Germany

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Abstract
The ALPQ field trial involved the preparation, execution, and interpretation of a mathematical model of a VPP which includes battery and biogas-fired assets as a simulation trial on the off-line version of the ALPQ VPP management system using historical data to feed the simulation. The mathematical modelling focused on managing the assets of the VPP so that the revenue they generate is maximised. The effects of optimising the operations of the VPP by applying the optimisations of weather forecasting to predictions of wind generated energy by a VPP, developed in WP3, is examined. The sensitivity of the level of revenue generated to changes in a range of input parameters to the model, including the parameter of varying the number, size and type of assets to be managed by the VPP, has been performed. The inclusion of battery storage and biogas-fired assets is specifically examined. The results of the modelling are expressed in terms of the level of revenue generated and the level of investment generated by the different versions of the model defined by varying the input parameters of the model regarding forecasting methods.

Keyword list
Virtual power plant, independent profits, inverted U-curves, power scheduling, day-ahead market, intraday market, EPEX SPOT, balancing, biogas power plant, battery, wind farm.

Executive Summary

In this deliverable, we focus on the optimisation of VPP operations through the testing of the new techniques in the ALPQ live VPP management system using historical data.

Furthermore, we explore aspects of the management of a VPP setup which manages assets including biogas power plants and a battery, focusing on maximising the VPP's profitability. This VPP provides balancing services for a set of wind farms while maximising the profits of the flexible assets.

For asset owners, an alternative to participating in a VPP with their collective assets under management is to manage the assets independently. In order to attract a flexible asset to participate in a VPP, the profit achievable by the asset owner must exceed the *independent profit* (profit associated with the independent management of the assets). This is made possible through the use of optimised algorithms which redistribute surplus energy – when the wind farms produce in excess of the energy generation which had been predicted for them – so that this excess energy can be used to recharge battery storage, and any remaining excess energy (which exceeds the capacity of the battery) can be sold on the market.

The revenues from sale of the excess energy and from charging the batteries with the excess energy are used to ensure that the profit of each asset is higher than its *independent profit*; another part of these revenues is allocated to the manager of the VPP, whose purpose is to operate the VPP to:

- Ensure the growth of the VPP while maintaining the balance of flexible assets and RES;
- Ensure that balancing is carried out correctly;
- The remuneration of the VPP aggregator is commensurate with the extent to which the balancing task is fulfilled and with the size of the balanced RES portfolio.

It is emphasised that the balancing charge itself affects the revenue of the flexible assets. Instead of selling the power at a high market price, the asset may be forced to not take advantage of this opportunity because of the upcoming balancing charge (need for the fuel).

The contributions of this deliverable include:

- The equations from Deliverable 3.3 are used, but there is an additional equation which enables to charge the battery with the surplus energy of the wind farms;
- The code that implements the presented algorithms has been deployed in the edgeFLEX Platform and can be used by edgeFLEX partners;
- A sensitivity analysis is carried out to show how profits evolve based on the variation of different input parameters;
- Results show that optimisation algorithms presented in this study outperform the revenues of historical trades by 2%.

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1. Introduction

In this deliverable, we present the simulations of the virtual power plant (VPP) as a “trial”. Using historical trade schedules, the optimisation algorithm is run under a range of input parameter assumptions to define the level of profitability achieved and the impact of the parameters chosen on investment requirements. This allows us to back test the optimisation algorithm.

This VPP provides balancing services for a set of wind farms belonging to the VPP studied in this field trial (an illustration of which is shown in Figure 1) while maximising the profits of the flexible assets. The balancing burden can reduce the revenues of the flexible assets – many profitable opportunities may be missed because of the need to conserve fuel or because the charge level of the battery which could be used for the balancing task is not sufficient to enable its use on a particular occasion. On the other hand, if the wind farm produces more energy than it has predicted (or nominated), the income from the sale of this energy surplus can be redistributed in the VPP, and the assets can earn more than they would if they had operated only in the spot market.

Randomised prices and commercial price forecasts are used. The imbalance is assumed to be known because methods exist for forecasting the imbalance and the examination of the prediction of this variable is beyond the scope of this report. The proposed methodology can be used in systems where imbalance forecasts are used as input. The optimisation is carried out in the framework of model predictive control (MPC), which is described in detail in Deliverables 3.2 and 3.3.

Two notions are introduced in this study: *independent profits* and inverted U-curves. If an asset is not involved in any balancing task, and only trades on the day-ahead (DA) market, then its profit will be denoted as *independent profit*. The *independent profit* also equals to the profit of an asset that is involved in the balancing, but there is no imbalance: e.g., it was predicted that there will be no wind, and it happened. The inverted U-curve (an inverted parabola) shows how the profits evolve when the imbalance varies.

Figure 1 – A wind farm under VPP management

The optimisation in this deliverable is based on the equations (the constraints of the optimisation problem) from Deliverable 3.3, but there is an additional equation which enables to charge the battery with the surplus energy of the wind farm.

This research focuses on the maximisation of profit from operations in the DA market of European Power Exchange (EPEX SPOT), but this logic can be extended to the case of the intraday (ID) blind auction, and the ID continuous market.

The conclusions from the sensitivity analysis carried out in this study may be used as basis for investment decisions.

1.1 Related work

The VPP optimisation work on which this deliverable is based was carried out as part of D3.2 Report on VPP optimisation, V1, and its successor D3.3 Report on VPP optimisation, V2. The two deliverables explore the optimisation of VPPs, consisting of a portfolio of biogas power plants and a battery whose goal is to balance wind farm production while maximising their revenues. Optimisation methods use price and imbalance forecasts as inputs and conduct parallelisation, decomposition, and splitting methods to handle sufficiently large numbers of assets in a VPP. The focus is on the speed of computing optimal solutions of large-scale mixed-integer linear programming problems, and the best speed-up is in two orders of magnitude enabled by the Gradual Increase method.

Subsequent to the reading of this deliverable, a deeper dive into VPP business models can be done with D6.1 Comparative Analysis of Potential Business Impact, V1 and its successor D6.1 Comparative Analysis of Potential Business Impact, V2. D6.1 introduces the edgeFLEX approach to combine technological approaches with organisational structures in order to provide more flexibility in the European electrical network, at a moment when the need to mitigate fluctuation in power generation due to the increasing share of intermittent energies in the electrical mix in Europe becomes crucial. In D6.2, two business scenarios are presented, based on two evolutions of the VPP:

- VPP 1.1, and enhancement on the current implementation of the VPP;
- VPP 2.0, a DSO centric VPP, that engages community assets and details a process to assess them.

1.2 The goal of the edgeFLEX VPP optimisation trials

The main objective of the edgeFLEX VPP optimisation trials is to demonstrate the increased profitability generated by the assets involved in a VPP when the optimisations developed in edgeFLEX are applied to its operations.

It should be attractive for owners of the flexible assets to join a VPP. In the framework of this simulation, the VPP consists of biogas assets and aims to maximise profits while providing balancing services to wind farms. If the flexible assets are not included in a VPP, the profit generated by the independent operation of their assets (i.e., when they are not involved in the management of a wind farm fleet) is the benchmark – this value must therefore be exceeded. It is shown that this goal can be achieved by exploiting the surplus of energy produced by the fleet of wind farms managed by the VPP. The owners of the wind farms inform the operator how much energy they will produce – this information is based on their production forecasts. The difference between the realised and forecast production is the imbalance that the VPP must handle. If they produce more than they forecast, it must be met by recharging the battery or by selling that energy in the ID market.

In this study, we assume that the excess energy is sold for a fixed price: this can be realised in practice and is useful for the sensitivity analysis. The question is: what excess energy price would make the cumulative profit of the assets when they are part of the VPP higher than the cumulative profit of independently managing each asset without any burden to balance the wind farms. This will enable the asset manager to guarantee the owners of flexible assets that there is a high likelihood that their profits will be larger. This can lead to a virtuous circle: if more wind farms are managed, then more revenue from the sale of the surplus energy will be achieved. However, since the flexible assets (e.g., biogas plants or batteries) have a high balancing burden, their profits from the trading can be reduced: instead of the sale of the power at a high price, they might have to spare the fuel in order to enable balancing. The inclusion of a new biogas plant or a battery reduces this effect. In other words, there are parameters settings within a VPP for which it becomes profitable for the participants to include new flexible assets since this might reduce their costs. There are also parameters for which it becomes profitable for the flexible assets that new wind turbines are included.

The profit of the VPP consists of three parts:

$$\mathrm{Profit}(Flex, Wind) = \mathrm{Rev}(Flex) - \mathrm{Cost}(Wind[D]) + \mathrm{Rev}(Wind[S])$$

Where *Flex* and *Wind* denote the new portfolio of assets of flexible or wind assets, respectively; *Wind[D]* and *Wind[S]* respectively denote the deficit and surplus energy.

The deficit has to be compensated for the market price; the surplus is usually sold at a fixed price within a long-term contract e.g., with miners of cryptocurrency, or producers of aluminium, etc.

The aim of the operator of the VPP is to increase *Flex* and *Wind* in such a way that:

$$\mathrm{Profit}(Flex', Wind) > \mathrm{Profit}(Flex, Wind) \text{ or } \mathrm{Profit}(Flex, Wind') > \mathrm{Profit}(Flex, Wind)$$

Wind' denotes the new portfolio of the wind assets after the decision to expand or reduce it; in an analogous manner, *Flex'* is defined i.e., the addition or removal of new biogas assets or batteries.

In this study, we explore these functions in detail and demonstrate how the above-mentioned target can be achieved for the presented set of assets, and how this logic can be used for another general set of assets.

A software, which uses the optimisation code and selected inputs, including historical data for back-testing, is introduced. Sensitivity analyses are also completed and reveal which parameters affect the profitability to what extent, and if corresponding investments can help achieve this goal.

These considerations relate to the creation of the virtuous circle when the VPP is naturally incremented by new participants and the participants tend to invest in renewable energy sources (RES) because those sources of energy will enable them to increase their profits within this framework.

1.3 How to read this document

In Section 2, the VPP optimisation carried out in edgeFLEX and back tested in this deliverable is put in perspective in the context of the evolution of VPPs, introducing the concepts of VPP 1.0 and VPP 1.1 and their relationships to the energy markets, the grid and fifth-generation wireless (5G) communications.

In Section 3, the optimisation problem and its environment are described. A description of the assets, input data, and the states of the system (storage levels and the states of the turbines) is provided. This section also provides the notation of all variables and constants, formulates the optimisation problem, and describes all the constraints of the optimisation.

Section 4 describes the software interface implemented for the VPP optimisation trials as well as the inputs used, including the use of different setups of the VPP and that of historical trading schedules.

Section 5 presents the results of the simulation trial and provides some sensitivity analyses of the profit output, varying parameters such as the maximum production, the capacity, etc. These results can be used in the decision-making regarding investments into flexible assets.

Section 6 is about the nuances of this trial such as 5G, grid support and regulatory frameworks.

Finally, the conclusions of this work are provided in section 7.

2. edgeFLEX VPP optimisation in the context of the evolution of VPPs

In this section, the concepts developed by edgeFLEX to describe the evolution of VPPs are briefly presented. The research undertaken in edgeFLEX to optimise VPP operations, and described in this deliverable, is related to their role in enabling the evolution of VPP envisaged by edgeFLEX.

2.1 edgeFLEX VPP evolution concepts

edgeFLEX has developed a brief description of VPP operations with three evolutionary steps to provide a context for understanding how the research results developed in edgeFLEX can be applied to enable the evolution of VPP operations to provide an increasing contribution to stabilising the grid by adding functionality to the VPP. The edgeFLEX envisaged evolution of the VPP is described in Figure 2 below.

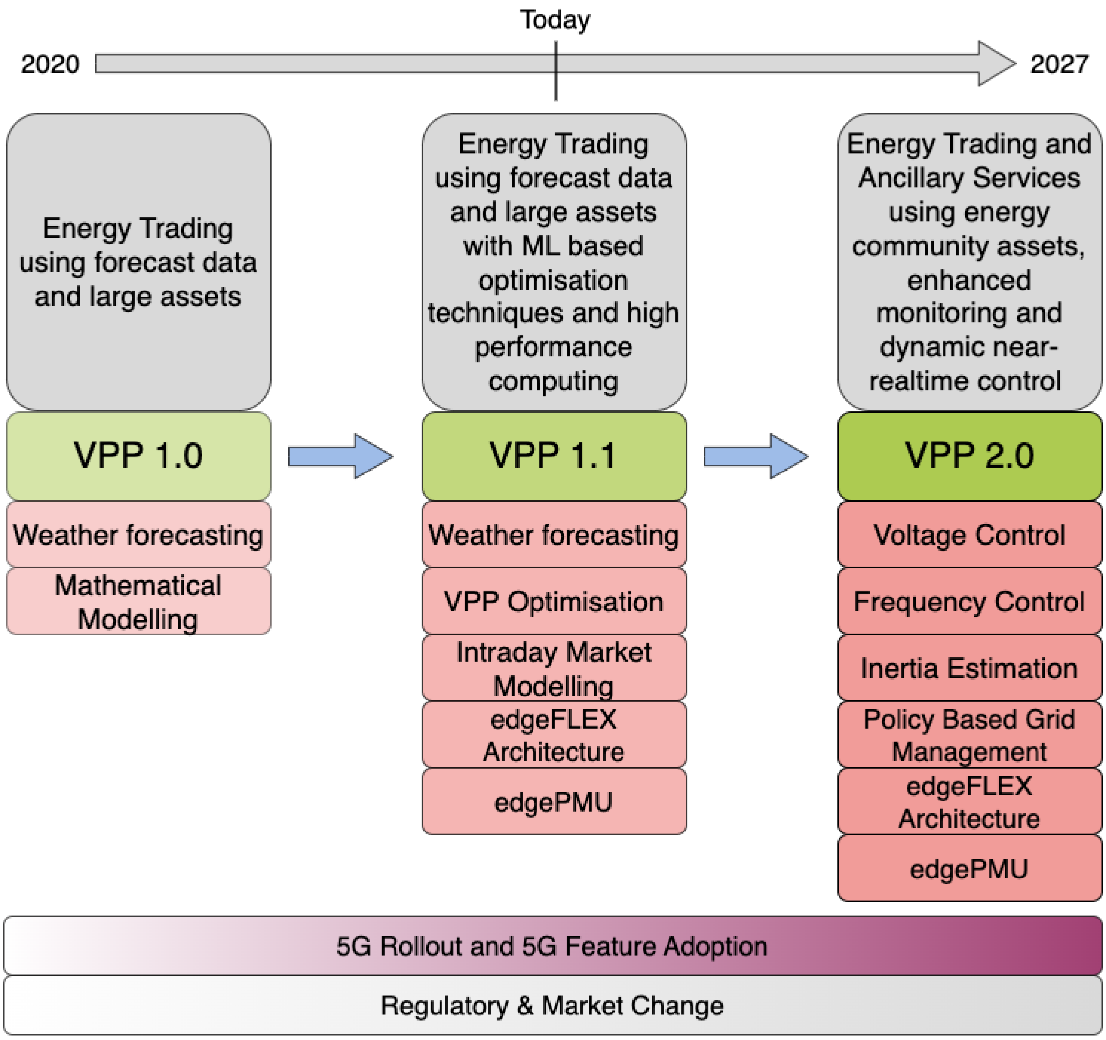


Figure 2 – The edgeFLEX proposed evolution of VPP operations contributing increased flexibility to the grid

2.1.1 The edgeFLEX VPP 1.0 and 1.1 concepts

The VPP 1.0 concept describes the basic operations of a VPP while the VPP 1.1 concept describes the efforts of many of the leading VPP operators to enhance the effectiveness of their operations using a range of techniques which can be applied commercially today, without the need for regulatory change.

The edgeFLEX optimisation of VPPs described is this deliverable provides a key element enabling the realisation of the VPP 1.1 concept, as described in Figure 2 above.

Compared with the original VPP 1.0 concept covering the basic and historically used functionality and operations of a VPP, the VPP 1.1 concept includes AI-based optimisation techniques enabling improved trading revenues to be made by VPPs in both the energy and capacity markets. These optimisation techniques, along with stochastic weather forecasting, ID market modelling as well as edgeFLEX architecture and edgePMU, are designed to improve the trading activities of VPPs in an environment with increasing RES penetration.

The relationship of VPP 1.1 to energy markets

The optimisation of VPPs as envisaged in the VPP 1.1 allows the aggregator to improve its participation in the different energy markets. Since the edgeFLEX optimisation of VPPs makes it possible to manage many different classes of assets, the aggregator can participate not only in the energy markets (such as the ID/DA markets) but also in the capacity markets, such as those for ancillary services.

The relationship of VPP 1.1 to its impact on the grid

The impact of an optimised VPP 1.1 is advantageous for both the aggregator and the grid operator. Indeed, it has been shown that an optimised VPP leads to a more balanced portfolio and to optimised revenues not only from energy market arbitrage but also through lower balancing charges. This improved balancing of the system also benefits the grid operator since its balancing efforts will be reduced. If this impact were to be generalised – through an increased number of VPPs in the system, one could expect substantial cost savings in grid infrastructure works and improvements, which the grid operator would otherwise need to complete.

The role of 5G in supporting VPP 1.1

Fourth-generation wireless (4G) (long term evolution, LTE) and 5G Mobile Networks can provide excellent support for the cost-effective operation of optimised VPP 1.1 systems. Their main communication requirement is for communications to the assets under management, to monitor and control their operation. Large-scale systems may implement both cabled and mobile communications to their key assets to ensure redundancy in the communications links so that should one network not be available, the second network can be used as an alternative means of communications. This redundancy in network availability reduces the risk to a VPP operator of losing transparency on the operations of the assets and of losing control of the assets, potentially resulting in penalties for the VPP operator.

2.1.2 The edgeFLEX VPP 2.0 concept

The most advanced operations of VPPs envisaged by edgeFLEX, enabling them to contribution to voltage and frequency control, to inertial estimation and to manage the small assets of Energy Community members require the implementation of new techniques for advanced monitoring of assets and services providing dynamic, near real-time control. Such advanced VPP operations are termed VPP 2.0 by edgeFLEX and their full implementation requires significant changes in the currently applied regulatory frameworks before commercial operation of such a VPP could be undertaken. The results of edgeFLEX research on voltage and frequency control and on inertial estimation as well as the edgeFLEX edgePMU are key enablers for the VPP 2.0 concept. The availability of 5G networks to support the near real-time communications with low latency and support for providing computational resources and information and communications technology (ICT) storage at the edges of the power grid will enhance the financial viability of such a VPP and reducing or eliminating the need for laying cabled communications to all of the many small assets under management by the VPP.

The role of 5G in supporting the evolution of VPPs toward the VPP 2.0

As large synchronous power plants leave the energy system the need for balancing the network increases. In the future, large VPPs could provide balancing services at the transmission system operator (TSO) level. To facilitate this, there will be a need to push services such as Frequency

Control closer to the edge of the medium-voltage (MV) / high-voltage (HV) network. To enable this, computational resources at the edge (or periphery) of both the grid and the communications networks will be needed to support virtualised services, such as those of the edgeFLEX edgePMU. 5G edge cloud infrastructure could provide support for these services meeting the communications and computational requirements of the services.

The availability of 5G Advanced Networks with their Ultra Reliable Low Latency Communications (URLLC) features support the most advanced implementations of the edgePMU services, enabling more frequent analysis of the data collected by the edgePMU and hence enabling precise, and also if desired distributed, network management decision making.

The edgeFLEX proposed VPP evolution is described in more detail in Section 2 of deliverable 6.2.

2.2 Conclusion on edgeFLEX VPP optimisation in the context of the VPP evolution

VPP optimisation has been a key element in reaching the current VPP 1.1 concept. Furthermore, on top of leading to increased revenue for the VPP aggregator and asset owner – through increased revenue in the energy market and the offsetting of negative imbalances, optimised VPPs also lead to less effort for the grid operator.

In the future, as large VPPs look to provide frequency and inertia support to the transmission grid, a finer grained control will need to be deployed to the edge. 5G would support this by providing edge cloud and reliable communications at the site of the assets with a secure link to the central control.

3. The edgeFLEX VPP optimisation problem description and formulation

This section first describes the different environments in which the assets are optimised as well as the key drivers of VPP revenue; it then provides description of the different assets in the VPP setup; finally, it provides the notation as well as the optimisation problem formulation and the main constraints.

The content of this section has been initially described in Deliverables 3.2 and 3.3; however, a number of additions have been made in this report. Whilst the optimisation in this deliverable is based on the equations from Deliverable 3.3, there is an additional equation which enables to charge the battery with the surplus energy of the wind farm.

3.1 Power markets and the balancing task

All assets considered in this study operate in the EPEX SPOT market. Their aim is therefore to maximise profits from balancing wind farms. EPEX SPOT consists of two markets: the DA market and the ID market. The first is a market where a blind auction is held, and the price is the same for every participant. This is called the market clearing price. The price is locked in for the next day. The ID market allows positions on the DA market to be adjusted and short-term forecasts to be exploited. The ID market consists of two parts: the auction, which functions in the same way as the DA auction, and a continuous market where trading takes place up to five minutes before delivery and where each participant is a price maker. The prices in the DA auction are not known in advance, so price forecasts are used when operating in the DA market. ID prices are known to be more volatile than DA prices, but they are centred around DA prices.

In this study, commercial price forecasts are used (the details about these price forecasts are not disclosed due to confidentiality issues). The same DA prices are used for ID prices. It is important to optimise against prices because it allows the owners of flexible assets to earn, and they will otherwise not be willing to join a VPP if it is not profitable. Solar and wind power production is dependent on weather conditions and therefore flexible assets are needed to cover the imbalance. The purpose of the flexible assets is to maximise profit while covering the imbalance equal to: *Realised Production – Predicted Production*. The imbalance is difficult to predict for the DA market, but the decisions made in the that market can be adjusted in the ID market. In other words, the inaccuracy in the forecasts of imbalance can be mitigated by simple operations in the ID market. There are two inputs for the optimisation:

- The vector of price forecasts on the DA market $Frc_t^{DA},\ t = 1,2,\dots,T$ where T is the prediction horizon;
- The vector of imbalance $IB_t,\ t = 1,2,\dots,T$ where T is the prediction horizon.

If $Frc_t^{DA} < 0$, then $IB_t = IB_t^-$ i.e., the vector of imbalance is equal to the negative part of the number IB_t. If the forecasted market price is below zero, it means that the grid is overloaded and that therefore additional injections are costly for both: the VPP and the grid. Such situations are handled in the ID market.

3.2 Features of the intraday and day-ahead markets

On the EPEX SPOT market, there are two trading systems: the system for managing blind auctions on the DA and ID markets – EPEX Trading System – and the system for the continuous ID market, called M7. EPEX Trading System is operated by the Deutsche Börse Group. It collects market orders in the limit order book (LOB). The sell orders from the LOB form the demand curve and the buy orders form the supply curve. The intersection of the demand and supply curves produces the market clearing price (MCP). This principle is applied to both auctions: the DA auction and the ID auction, and in both cases, the Euphemia algorithm is used. On the continuous ID market, the orders are collected in the order book and once the matching opposite order is found, the settlement between buyer and seller takes place. Some orders are not executed on this market due to the lack of the matching counterpart orders. This order book is stored and managed by the M7 system.

For small participants in the DA market, it is possible to use price forecasts to nominate the volumes of electricity produced. This approach is used in this study. In general, it is possible to use optimisation to generate price-volume bids. In our simulations, we use ID-3 (average over the last three hours) prices in the ID market for price estimation. As a subject of further research, we consider the use of the full order book stored in the M7 database for operations in the continuous ID market where decisions are made using optimisation.

3.3 Appearance of prices

On the DA market, prices appear in batches: 24 price instances for the next day. This is why this market is called DA. When trading on the DA market, participants must take into account that they first take positions (i.e., they buy or sell at a certain price) and find out the next day whether they were successful or not. This makes price forecasting in the DA market crucial.

ID prices are usually centred around the DA prices as is shown in Figure 3. However, the ID price is averaged over either the last hour (ID-1) or the last three hours (ID-3).

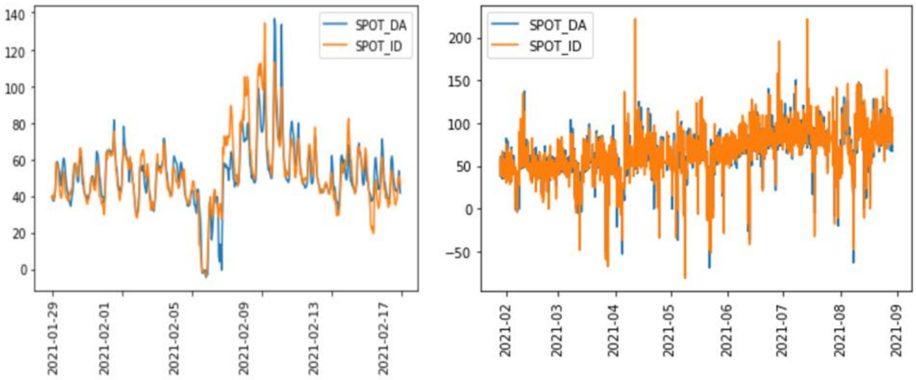


Figure 3 – Visualisation of prices on DA and ID markets; left: from 29/01/2021 to 17/02/2021; right: from February to September 2021

3.4 Data download

The data inputs are downloaded from the Alpiq AG (ALPQ) databases via a representational state transfer (REST) based time series application programming interface (API) using the Python package 'requests'. The following input types are downloaded from the database:

- Actual data: prices and wind productions;
- Forecast data: prices and wind productions.

The API represents every time series using an individual uniform resource locator (URL). For example, https://awb.alpiq.io/AWB/GermanySpotPriceForecast refers to a spot price forecast.

3.5 Price forecasts

Price forecasts are crucial for the optimisation of portfolios of biogas power plants and batteries. On the DA market, the decisions are made before prices are known, therefore it is important to possess forecasts. The procurement of the forecasts can be obtained in two ways:

- Using commercial price forecasts which might be costly, however they are often part of a large batch of products, and their resulting price is then lower.
- Elaboration of forecasts using prediction tools based on methods of time series analysis and using methods such as deep learning, gradient boosting, etc. The commercial forecasts can also be used to improve the asset owner's own forecasts.

More detail about explanatory variables, namely calendar data, fuel prices, residual load, the data about available generators is provided in the following sections. The different methods for machine learning and forecasting are also introduced.

3.5.1 Calendar data

Calendar data affect both the electricity consumption and price: both prices and the consumption have seasonal effect. For example, during a working day, there is more consumption than during the weekend or a public holiday; or during the winter more energy is spent on heating, etc. There exist typical weekly patterns, where on the weekend the electricity production and price are lower than on the working days, and at the peak hours, the load and the price are usually higher. Apart from the working day and the weekend, the following dates are important:

- National holidays, especially Christmas, New Year, Easter, etc.;
- Bridge days;
- School vacation: when children have vacation, the parents may tend to take vacation at work;
- Seasonality: e.g., in summer it might be necessary to air-condition houses, in winter, it might be necessary to heat buildings.

3.5.2 Fuel prices

Fuels such as coal or gas are used in the production of electricity and represent a major part of the cost of production.

3.5.3 Residual load

The residual load is defined as follows:

ResidualLoad (MWh) = TotalLoad (MWh) – SolarProduction (MWh) – WindProduction (MWh)

This is the part of the total load that was not covered by the most important RES and this value affects the work of the conventional and flexible energy sources.

3.5.4 Available generators

The availability of generators is also important for both price and load forecasting. Generators may break down. They also need regular maintenance, and these events need to be announced. If high demand coincides with a large number of generators under maintenance, there is a risk that demand cannot be met, which would increase the price. Therefore, price forecasts take these variables into account.

3.5.5 Machine learning methods used in electricity price forecasts

The following machine learning techniques can be used for the forecast of prices:

- DeepAR;
- N-BEATS;
- Multichannel singular spectrum analysis (mSSA);
- XGBoost;
- Long short-term memory (LSTM);
- Conformal Predictions;
- Hybrid models.

3.5.6 The choice of forecasting methods for use in optimisations

Out of all candidates, either the best is chosen (according to some predefined metric), or a combination of the forecasts is used to produce a better forecast: an attempt to achieve a synergic effect.

In this report, commercial price forecasts are used because they perform better than most other forecasts in the most adequate metrics.

3.6 The role of wind production forecasts in VPP optimisation

In Deliverable 3.2, the analysis of the wind production forecasts is presented. The most important element that emerges from this analysis is the approach to the data: the measuring units are often located far from the wind farms. Moreover, they are not located at the altitude characteristic of wind turbines. As a result, the quality of the prediction is strongly affected. Table 6 in Deliverable 3.2 shows how the relative error decreases as the distance between the wind farm and the nearest weather station decreases. In the optimisation, the difference between the actual and the predicted production is taken into account as the imbalance: the more accurate the predictions, the smaller the load on the flexible assets, and thus the higher the profit of the VPP, and the lower the imbalance cost for the wind farm.

However, in order to realise this idea, a whole infrastructure project for the implementation of measurement devices needs to be conducted. It is not sufficient to simply use a successful machine learning method. And as the data show, if this project is implemented, a significant reduction in imbalance is possible. And consequently, it could be a topic for investment.

3.7 Description of the assets used in the edgeFLEX VPP model and trial

3.7.1 Overall VPP portfolio description

The VPP is made up of a portfolio of four biogas power plants and a battery, whose goal is to balance the production of wind farms located in four regions of Germany. These assets are described in Deliverable 3.2 and [1]; however, in this deliverable, a more detailed description is provided. Note that the names of the biogas plants, the batteries, and the wind farms are not disclosed for reasons of confidentiality.

The purpose of the pool of biogas plants and batteries is to address the cumulative imbalance. Operational data for four biogas power plants and one battery was collected.

The turbines within the biogas power plants have no typical timing constraints (minimum on and off time) except for the condition that the maximum number of switches per year is limited to 1500. When exploring the computational speed of our algorithms, timing constraints are imposed because they are typical for the turbines. The process of the biogas production is outsourced, and it is assumed that there is a constant inflow of the biogas into the storage. The fuel costs are assumed to be fixed.

For the pools of assets, the impact of scaling is tested to explore how the increasing number of assets affects the speed of the calculations: when scaling the pools of assets, the number of assets is predefined and the storage capacities, gas inflows, maximum and minimum productions of the turbines (*Pmax, Pmin*) and minimum on and off times for the turbines within biogas power plants (timing constraints) are randomly assigned. In the scaling of the pools of flexible assets, the size of wind farms increases proportionally. This enables us to apply the proposed algorithms to a broader scope of asset types.

We operate on the German market EPEX SPOT (DA and ID markets) and use the price forecasts as objective value coefficients.

In the biogas power plants, the processes of realised production and electricity production are separated. The operators of the assets are guaranteed to obtain fixed amounts F_k of biogas (measured in MWh) in every period and they concentrate only on electricity production. In this study, biogas power plants with heating rods (combined head and power) are not considered.

In Table 1, the description of the assets and their schematic parameters is provided (without sharing their parameters due to confidentiality issues). The parameters of the first turbine of the first biogas power plant (*Biogas 1*) will be denoted as follows: the maximum produced power per hour will be denoted *Pmax*. The capacity of the first power plant (*Biogas 1*) will be denoted *C*. The rest of the parameters will be described using these symbols. There are four biogas power plants: *Biogas 1* to *Biogas 4*, and all of them have exactly one storage facility whose capacity is proportional to *C*.

Table 1 – Biogas assets

Biogas 1		
	Pmin	Pmax
Turbine 1	0.5*Pmax	**Pmax**
Turbine 2	1.75*Pmax	3.5*Pmax
Capacity	**C**	
Gas inflow	1.07 * **Pmax**	
Biogas 2		
	Pmin	Pmax
Turbine 1	**Pmax/2**	**Pmax**
Turbine 2	0.32*Pmax	0.63*Pmax
Capacity	0.83*C	
Gas inflow	0.86 * **Pmax**	
Biogas 3		
	Pmin	Pmax
Turbine 1	**Pmax/2**	**Pmax**
Turbine 2	1.75* **Pmax**	3.5* **Pmax**
Capacity	**C**	
Gas inflow	1.07 * **Pmax**	
Biogas 4		
	Pmin	Pmax
Turbine 1	2.02*Pmax	4.03*Pmax
Turbine 2	0.7*Pmax	1.4*Pmax
Turbine 3	0.7*Pmax	1.4*Pmax
Turbine 4	0.35*Pmax	0.7*Pmax
Capacity	3.25 * **C**	
Gas inflow	3.27 * **Pmax**	

3.7.2 The battery

The battery is located in Germany (Bavaria) and is mainly used in the balancing energy market, also has a grid protection function: it has participated in preventing two blackouts. The data about this battery is used the presented calculations.

3.8 The notation

Prior to the formulation of the optimisation models, a specific notation is required; this is provided in Table 2 and Table 3 below.

Table 2 – Notation: constants

Symbol	**Explanation**
$\#A$	Number of assets
C_{ki}^{w}	Cost of switching-on of Turbine i of asset k (EUR)
C_{ki}^{v}	Cost of switching-off of Turbine i of asset k at time t (EUR)
$DT^{(k,i)}$	Minimum off time of Turbine i of asset k (hours)
E_k^{max}	Maximum storage of asset k (MWh)
f_t^*	Amount for which the operator sells the excess energy
F_k	Flow of biogas power plant k every 15 minutes (MWh)
$Frc_t^{(DA)}$	Day-ahead price at time t (EUR/MWh)
IB_t	Vector of imbalance
$Pmin_{ki}$	Minimum power of turbine i of asset k (MW)
$Pmax_{ki}$	Maximum power of turbine i of asset k (MW)
Spt_t	Ideal value for which the operator sells the excess energy
$\#U(k)$	Number of turbines within asset k
$UT^{(k,i)}$	Minimum on time of Turbine i of asset k (hours)
η_k^d	Efficiency of the discharge of battery k
η_k^c	Efficiency of the charge of battery k
$\forall t,k,i$	Shorthand for: for all $t \in \{1,\dots,T\}$ and all $k \in \{1,\dots,\#A\}$ and all $i \in \{1,\dots,\#T(k)\}$

Table 3 – Notation: Variables

Symbol	**Explanation**
f	Penalty for the surplus energy (EUR)
f_1	Fee for the charging of the battery (EUR)
$p_{t,k,i}$	Total power produced at time t by turbine i of asset k (MW)
$p_{t,k,1}^d$	Discharge of battery k at time t (MWh)
$p_{t,k,1}^c$	Charge of battery k at time t (MWh)

$p_t^{C,cs}$	Total amount of the surplus energy used to charge the battery (MWh)
$soc_{t,k}^{Bg}$	Storage level of asset (power plant) k at time t (MWh)
$soc_{t,k}^{Bt}$	Storage level of asset (battery) k at time t (MWh)
$TotalPower_t$	Total power produced by all assets at time t (MW)
$TotalVcost_t$	Total switch-on costs produced by all assets at time t (MW)
$TotalWcost_t$	Total switch-off costs produced by all assets at time t (MW)
$u_{t,k,i}$	State of turbine i of asset k at time t
$v_{t,k,i}$	Switch-on decision of turbine i of asset k at time t
$w_{t,k,i}$	Switch-off decision of turbine i of asset k at time t
x_k	Set of all variables p, u, v, w, soc, p reduced to asset k
y_t	Set of all variables p, u, v, w, soc, p reduced to time t
z^*	Optimal value of variables z. Any variable superscripted with a star denotes the value optimal for the objective function
z_t^d	Deficit energy (MWh)
z_t^s	Surplus energy (MWh)

3.9 VPP optimisation formulation

In this section, the objective of the VPP optimisation as well as the mains constraints for the biogas plants and batteries are presented. The optimisation problem formulation is then provided, followed by the description of the independent profit as well as an explanation of the objective value coefficients and the framework.

3.9.1 The objective of the VPP optimisation

The objective is to maximise the profits of pools of biogas power plants and batteries while balancing the wind farms and taking technical constraints into account. The technical constraints of the turbines include their maximum and minimum production per period, their timing constraints, and the storage levels of the fuel. As for the batteries, the technical constrains are the charge levels.

The objective to be maximised is as follows:

$$\sum_{t=1}^{T}\left(Frc_t^{(DA)} \cdot p_t^C - v_t^C - Frc_t^{(DA)} \cdot z_t^d - w_t^C - f \cdot z_t^s - f_1 \cdot p_t^{C,cs}\right) \tag{1}$$

where $\mathrm{mean}(Frc) > f > f_1$, and the variables in the objective are represented by the following equations:

$$p_t^C = \sum_{k=1}^{\#A} \sum_{i=1}^{\#U(k)} p_{t,k,i}\,, \qquad p_t^{C,cs} = \sum_{k=1}^{\#A} \sum_{i=1}^{\#U(k)} p_{t,k,1}^{cs},$$
$$v_t^C = \sum_{k=1}^{\#A} \sum_{i=1}^{\#U(k)} C_{ki}^{v} v_{t,k,i}\,, \quad w_t^C = \sum_{k=1}^{\#A} \sum_{i=1}^{\#U(k)} C_{ki}^{w} w_{t,k,i}\,. \tag{2}$$

The variables z_t^d and z_t^s take non-zero values when the capacity of the VPP is not sufficient to satisfy the coupling constraint.

The revenues from the sale of energy on the market are optimised. In the case of a battery, every switch-on and -off with costs C_{ki}^{v} and C_{ki}^{w}, are zero.

The constant T denotes the prediction horizon that is used for the optimisation and $Frc_{t}^{(DA)}$ is the forecasts of DA prices at time t.

3.9.2 The constraints introduced by biogas plants and batteries

This subsection describes all constraints related to biogas plants and batteries. All these constraints are based on the equations from [1] and Deliverable 3.2 except for constraints for the battery that enable it to charge with the surplus energy produced by the wind farms, i.e., Equation (9).

3.9.2.1 Binary constraints

In this report, *3bin* formulation is employed, and all u, v, and w variables are binary, therefore:

$$u_{\{t,k,i\}}, v_{\{t,k,i\}}, w_{\{t,k,i\}} \in \{0,1\} \quad \forall\, i,k,t. \tag{3}$$

3.9.2.2 Constraints for the biogas power plants

In this subsection, all the constraints associated with biogas power plants are provided.

3.9.2.2.1 Power Constraints

For every turbine there are two basic values: $Pmin_{ki} > 0$ and $Pmax_{ki} > Pmin_{ki}$, which implies that it can either do nothing or produce within the interval $[Pmin_{ki}, Pmiax_{ki}]$ i.e.

$$p_{t,k,i} \in \{0\} \cup [Pmin_{ki}, Pmax_{ki}] \quad \forall\, t,k,i \tag{3b}$$

These constraints can be written using the $u_{t,k,i}$ variables which equal 1 if at time t the i-th turbine of asset k is on and it is 0 otherwise:

$$p_{t,k,i} - Pmin_{ki}\, u_{t,k,i} \geq 0, \qquad Pmax_{ki}\, u_{t,k,i} - p_{t,k,i} \geq 0 \quad \forall\, t,k,i. \tag{4}$$

3.9.2.2.2 Storage constraints

Every biogas power plant k has its own storage and a constant flow of gas F_k (expressed in MWh) into it. The new storage level is equal to the old level added by F_k and subtracted by the aggregate energy produced by all turbines within asset k during one period:

$$soc_{t,k}^{Bg} = soc_{t-1,k}^{Bg} + F_k - \sum_{i=1}^{\#U(k)} p_{t,k,i} \cdot \Delta t \quad \forall\, t,k, \qquad \Delta \mathrm{t} = 15 \text{ minutes} \tag{5}$$

and there are the box constraints:

$$soc_{t,k}^{Bg} \in [0, E_k^{max}] \quad \forall t,k. \tag{6}$$

3.9.2.2.3 Timing constraints

The on and off decisions for the turbines are conducted via binary switch-on (v) and binary switch-off (w) variables as follows [16]:

$$u_{t,k,i} - u_{t-1,k,i} = v_{t,k,i} - w_{t,k,i} \quad \forall\, t,k,i. \tag{7}$$

If at time t a turbine i of asset k is on or off than it has to be on or off for at least $UT^{(k,i)}$ and $DT^{(k,i)}$ periods, respectively, which is exressed as follows:

$$\sum_{j=t-UT^{(k,i)}+1}^{t} v_{j,k,i} \leq u_{\{t,k,i\}} \text{ and } \sum_{t-DT^{(k,i)}+1}^{t} w_{j,k,i} \leq 1-u_{t,k,i} \quad \forall\, t,k,i. \tag{8}$$

3.9.2.2.4 Timing constraints tuning

There are light requirements on the turbines of the biogas power plants: maximum number of switches per year. These conditions can be handled by imposing penalties for switch-ons and switch-offs. On the other hand, turbines generally have strict timing constraints, so in our research, timing constraints are deliberately imposed to broaden the scope of our algorithms. In any case, if it is possible to handle the timing constraints by penalisations C^v and C^w, we should do this because the constraints (8) account for most of inequality constraints of the problems and their removal can lead to significant reductions of the computation time.

3.9.2.3 The constraints for batteries

In this subsection, we write out all the constraints associated with batteries.

3.9.2.3.1 Power constraints

For every battery, the following power constraints exist. This differs from Deliverables 3.2 and 3.3 by the involvement of the variable $p^{cs}_{t,k,1}$:

$$\begin{gathered}
Pmax_{k,1}\, u_{t,k,1} - p^{d}_{t,k,1} \geq 0 \quad \forall\, t,k,\\
Pmax_{k,1}\left(1-u_{t,k,1}\right) - p^{c}_{t,k,1} \geq 0 \quad \forall\, t,k,\\
Pmax^{cs}_{t,k,1}\left(1-u_{t,k,1}\right) - p^{cs}_{t,k,1} \geq 0 \quad \forall\, t,k,\\
p^{c}_{t,k,1} - Pmin_{k,1}\, w_{t,k,1} \geq 0 \quad \forall\, t,k,\\
p^{d}_{t,k,1} - Pmin_{k,1}\, v_{t,k,1} \geq 0 \quad \forall\, t,k.
\end{gathered} \tag{9}$$

Constraints (10) ensure that we cannot charge and discharge at the same time. The update of the storage level and the state of charge is conducted as follows:

$$soc^{Bt}_{t+\Delta\, t,k} = soc^{Bt}_{t,k} + \Delta t \cdot \eta^{c}_{k} \cdot (p^{c}_{t,k,1} + p^{cs}_{t,k,1}) - \frac{p^{d}_{t,k,1}\Delta\, t}{\eta^{d}_{k}} \quad \forall\, t,k, \tag{10}$$

with $p^{d}_{t,k,1}$ constant in $[t, t+\Delta t]$ and Δt is always 15 minutes.

3.9.2.3.2 Tightening constraints

$$v_{t,k,1} \leq u_{t,k,1} \text{ and } w_{t,k,1} \leq 1 - u_{t,k,1} \quad \forall\ t,k, \tag{11}$$

and for all t there are the box constraints:

$$soc^{Bt}_{t,k} \in [0, E^{max}_{k}] \ \forall\, t,k. \tag{12}$$

3.9.2.3.3 Switches of the batteries

The on and off decisions for the batteries are conducted via binary switch-on (v) and binary switch-off (w) variables as follows:

$$u_{t,k,1} - u_{t-1,k,1} = v_{t,k,1} - w_{t,k,1} \quad \forall\, t,k. \tag{13}$$

3.9.2.3.4 Components of the objective function

We define the variables $p_{t,k,1}$ as follows:

$$p_{t,k,1} = p_{t,k,1}^{d} - p_{t,k,1}^{c} \quad \forall\, t, k, \tag{14}$$

which is included in the objective (1).

3.9.2.4 Coupling constraints

The coupling constraint is a task that all flexible assets must fulfil. This is given by the imbalance $IB_t \;\forall\, t$ between the realised and forecasted production of the intermittent sources. In the coupling constraint, the variables z_t^d and z_t^s are used: the former corresponds to the situation when the capacity of the system is no sufficient and the deficit is equal to z_t^d and it has to be bought on the ID market; the latter corresponds to the situation when the capacity of the battery is not sufficient to manage the entire surplus and this surplus is sold but it is sold for a fixed price f which is significantly lower than the market price:

$$p_t^C + z_t^d \geq \; IB_t^+ , \qquad p_t^{C*} + z_t^s \geq |IB_t^-| \qquad \forall\, t \tag{15}$$

Let us note that the right-hand side of (15) is the input that must be estimated. This boils down to estimating the imbalance which is a challenging task. In this report, it is assumed that the imbalance is known in advance. This approach is relevant in situations when the imbalance is known in advance: the topic of forecasts of imbalance exceeds the scope of this study.

3.9.3 Optimisation problem formulation

Summarising the constraints and objectives, we can formulate the optimisation problem with the forecast parameters: Frc^{DA}, Frc^{ID}, and IB as follows:

$$\text{maximise} \sum_{t=1}^{T} (Frc_t^{(DA)} \cdot p_t^C - v_t^C - Frc_t^{(DA)} \cdot z_t^d - w_t^C - f \cdot z_t^s - f_1 \cdot p_t^{C,cs}) \tag{16}$$

$$\text{s.t.} \qquad\qquad (2) - (15).$$

3.9.4 Independent profit

This sub-section defines the notion of *independent profit*. This is a profit, which is obtained in a situation when the assets do not balance any intermittent assets and are managed independently of each other. In this case the objective and the problem are as follows, and the result can be obtained by the concatenating the results from independent problems:

$$\text{maximise} \sum_{t=1}^{T} (Frc_t^{(DA)} \cdot p_t^C - v_t^C - w_t^C) \tag{17}$$

$$\text{s.t.} \qquad (2) - (15) \text{ excluding all the constraints with } z_t^d, z_t^s, \text{and } p_t^{C,cs} \text{ variables}$$

3.9.5 Explanation of objective value coefficients and the framework

In Section 3.9.1, it is stated that $\text{mean}(Frc) > f > f_1$. This is because the deficit is less detrimental than the surplus. The variables z_t^d have $-Frc_t^{(DA)}$ coefficients i.e., the missing energy will be purchased on the market for the market price. However, the surplus can be used to charge the battery and it can be sold on the market. Nevertheless, the uncovered surplus can be sold on the market. Therefore, it is less severe, and it is intuitive to assume that $\text{mean}(Frc) > f$. This surplus is desirable for those who can profit from its sale on the market, but it is undesirable for the owners of the wind farms and the grid. That is why, in the objective function, this surplus is penalised. However, in the settlement process this surplus enables to receive a profit which exceeds the *independent profit*. The part of the sales of the uncovered surplus energy ($p_t^{C,cs}$) that exceeds the fee is used by the operator of the VPP i.e., the flows to the operator are as follows:

$$\sum_{t=1}^{T}(f_t^* - f) \cdot z_t^s,$$

This amount is used for the operation of the VPP and the investments into RES and flexible assets. The amount

$$\sum_{t=1}^{T}(f \cdot z_t^s + f_1 \cdot p_t^{C,cs})$$

is distributed among the flexible assets to enable each asset to exceed its *independent profit*. It can easily be shown that if the usage of z_t^s is not penalised than the battery will balance the deficit only if it is profitable; in addition, the positive imbalance can be intentionally created. That is why in the objective function its objective value coefficient is negative. The setting of these parameters is delegated to the operator of the VPP, and the remuneration of this operator must be proportional to the value:

$$\xi = \left(1 - \frac{\sum_{t=1}^{N} z_t^d}{\sum_{t=1}^{N} IB_t^+}\right) \times \left(1 - \frac{\sum_{t=1}^{N} z_t^s}{\sum_{t=1}^{N} |IB_t^-|}\right) \times \sum_{t=1}^{N} IB_t^+ \times \sum_{t=1}^{N} |IB_t^-| \qquad (18)$$

The first and second factors of z are used motivate the operator to balance the wind farms. The third and fourth factors of ξ motivate the operator to increase the set of balanced assets i.e., the inclusion of new wind turbines increases these factors. Better wind production forecasts together with relevant optimisation parameters increase the first and second factors of ξ.

The inclusion of new assets also increases the first and second factors of ξ, because the positive values of z_t^d and z_t^s are caused by the insufficient capacity of the assets, and the addition of new assets increases this capacity.

Under such a setting, the VPP will grow in terms of the assets in the VPP and assets in the portfolio of the managed wind fleet.

Figure 4 illustrates the proposed framework.

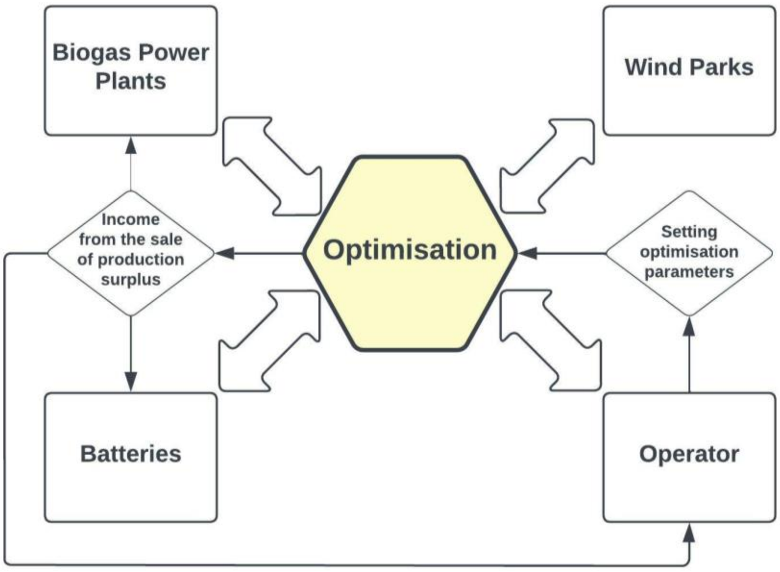


Figure 4 – The framework of the VPP

3.10 Conclusion on the VPP optimisation problem description

The VPP environment in manifold – it evolves on both the energy and capacity markets, with optimisation to be carried out in both those markets.

The price and weather forecasts are crucial to determine the production profiles; however, whilst price forecasts in the scales pertaining to this optimisation are accurate and predictable, this is not the case for weather forecast, and investment would be required in order to setup more accurate weather data stations.

The VPP optimisation formulation mathematically describes the objective of the VPP optimisation algorithm, which is to maximise the profits of pools of biogas plants and batteries while balancing the wind farms and taking technical constraints into account. All the results provided in this deliverable were simulated using the software, which uses the VPP optimisation formulation as algorithm.

4. VPP optimisation software interface and trial use cases

In the first part of this section, the infrastructure choices made in the preparation of the VPP optimisation trial is presented.

The background information collection regarding ALPQ's requirements and company system and security constraints relevant to the VPP optimisation is then provided.

Two use cases were carefully chosen to represent asset configurations and optimisation parameters likely to provide the maximum insights from the test of sets to be conducted:

- In use case 1, biogas assets and wind farms are the assets of the VPP used for the trial. The focus is on the compensation of the wind farm's negative imbalance by the biogas assets of a VPP;
- In use case 2, a battery is added to the biogas assets and the wind farms. The compensation of the negative and positive imbalance is optimised and additionally revenue on the spot market is generated as an extra objective.

For each use case, the interface developed in edgeFLEX to facilitate this trial is used to illustrate the input of the use case parameters to the optimisation algorithm.

The outcome of the trials with the two use cases in presented in the following section.

4.1 The choice of infrastructure chosen to support the edgeFLEX trials

The focus of the software implementation in edgeFLEX was to prepare the interface to the ALPQ off-line management system used to test improvements before deployment on the live VPP network. The off-line management system offers the same functionality as the live VPP management system, and it therefore forms an excellent infrastructure for conducting trials without generating the risk that the live operations could be disrupted in any way. The ALPQ VPP management system enables the user to decide which wind farms to manage, what assets to involve, and what time-period to employ for trials of new algorithms. Historical market and wind production data are available from one of ALPQ's databases, and this data can be integrated into the trials of use cases.

We have used m5d.4xlarge EC2 instance within Amazon Web Services (AWS) i.e., 16 virtual central processing units (vCPUs) and 64 gibibyte (GiB) random-access memory (RAM) in the execution environment. In the optimisation, the GUROBI solver was employed as part of the processing infrastructure used in the trials. To optimise a limited set of power production and storage assets the open-source coin-or branch and cut (CBC) solver was used. However, for bigger portfolios of assets, it is the commercial solver GUROBI was used.

A Python-based model logic is used to mediate among the databases, the APIs and the GUROBI solver. The runtime environment is executed in a lightweight AWS FARGATE container with no significant central processing unit (CPU), or memory resources allocated.

4.2 VPP optimisation trial planning started with requirements capture

Since the early stages of the edgeFLEX project onwards, it has been envisaged that the gathering of detailed requirements was key to developing the software and the platform as well as designing and developing it in a way that would ensure that it would be capable of being deployed in the planned edgeFLEX trials of the optimisations.

The careful elucidation and collection of these requirements by the developer of the VPP optimisation algorithm and the trial site staff ensured that the appropriate architecture could be developed, and the appropriate data streams and software implementation of the technique identified. One of the key requirements identified was the need to protect the company's boundary relating to the data that was being used to generate the outputs. This data is commercially sensitive and to expose this data outside the company's boundary would not be an acceptable solution for the stakeholders. Therefore, the need was identified to deploy the algorithm tightly coupled to the source of the price and forecast data with only the outputs of the algorithm (which cannot be reverse engineered to infer sensitive information) being exposed externally for monitoring within the edgeFLEX platform.

4.2.1 Definition of the VPP optimisation Functional Architecture

Figure 5 illustrates the functional architecture of the VPP optimisation and how the business sensitive data and the algorithm are deployed within the ALPQ company boundary and inside the security protocols and systems that protect the ALPQ systems and platforms. A set of pre-agreed data transfer protocols have been defined and developed so that the outputs of the algorithm could be integrated with the edgeFLEX platform for reporting and monitoring.

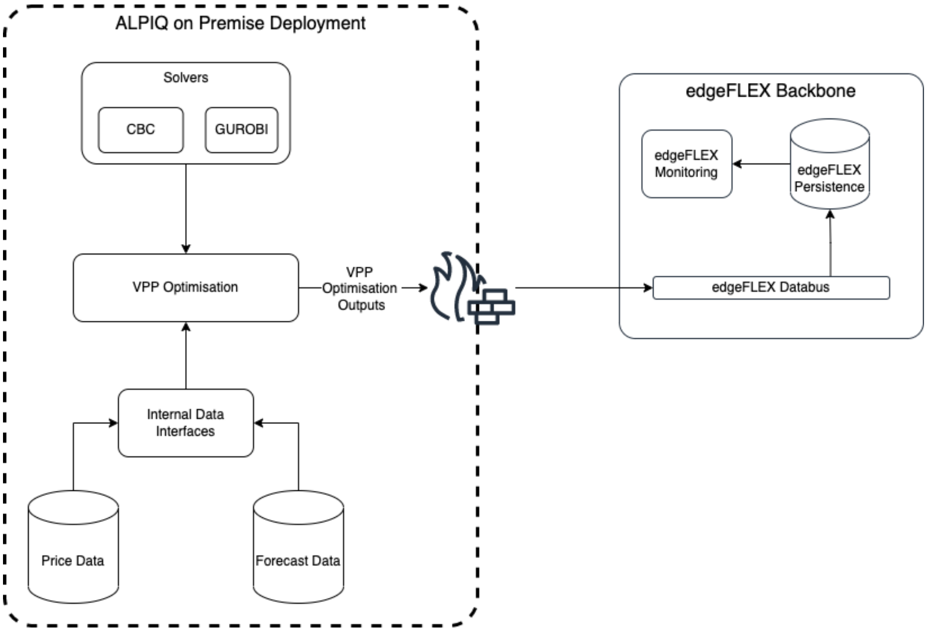


Figure 5 – VPP Optimisation functional architecture

The achievement of this type deployment is heavily reliant on taking a microservices approach to developing software and to enable the VPP optimisation algorithm to be deployed as part of an existing system without impacting on the workings of the system docker was used to build the algorithm into a docker container and by doing so it could be deployed in isolation and at runtime be configured to access the relevant data and utilise the required solvers without needing to provision dedicated virtual machines or extending existing architectures. This means that the algorithm can be portable and hooked into data streams in other companies with minor modifications or some middleware transformation functions that will manipulate the data to align to the input requirements of the algorithm.

4.3 Trial use case 1

In this use case, only the biogas assets and the wind farms are included in the simulation. This means that only the negative balancing of the wind portfolio is possible.

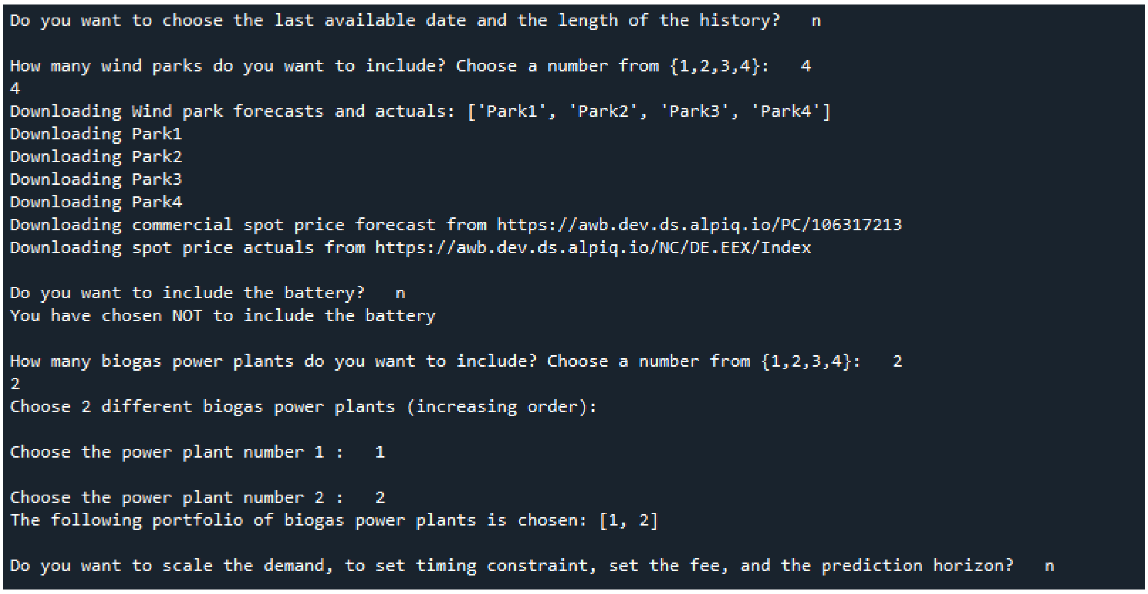
In Figure 6, an example of the data entry in the user interface for this particular use case is shown. For instance, the first question is whether a user desires to choose a period of interest: if so, the user is asked to choose this period; if not, then the last 12 days will be chosen i.e., the last 12 days are part of the default settings.

The second question is how many wind farms to include: since there are four wind farms, and the number four was chosen, then all wind farms will be managed.

The next question is if a battery must be included, and in the example in Figure 6 the battery is not included. The next question how many biogas assets to choose, and two was chosen and the program enables to choose the assets i.e., two different numbers from the set [1,2,3,4]. For this case, Biogas1 and Biogas2 were chosen.

The last question is whether a user desires to modify the parameters and inputs.

After the choice of the inputs, the optimisation is carried out in a MPC fashion, and the corresponding schedules are stored in an Excel file. This is explained in more detail in Deliverable 3.2.



```
Do you want to choose the last available date and the length of the history?   n

How many wind parks do you want to include? Choose a number from {1,2,3,4}:   4
4
Downloading Wind park forecasts and actuals: ['Park1', 'Park2', 'Park3', 'Park4']
Downloading Park1
Downloading Park2
Downloading Park3
Downloading Park4
Downloading commercial spot price forecast from https://awb.dev.ds.alpiq.io/PC/106317213
Downloading spot price actuals from https://awb.dev.ds.alpiq.io/NC/DE.EEX/Index

Do you want to include the battery?   n
You have chosen NOT to include the battery

How many biogas power plants do you want to include? Choose a number from {1,2,3,4}:   2
2
Choose 2 different biogas power plants (increasing order):

Choose the power plant number 1 :   1

Choose the power plant number 2 :   2
The following portfolio of biogas power plants is chosen: [1, 2]

Do you want to scale the demand, to set timing constraint, set the fee, and the prediction horizon?   n
```

Figure 6 – First trial use case as shown in the software

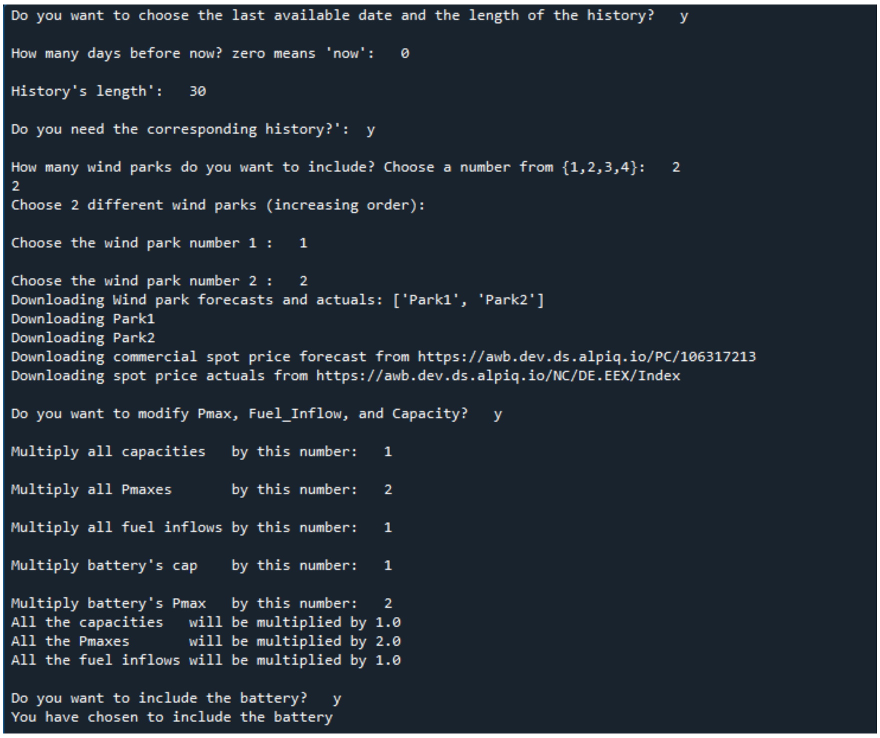
4.4 Trial use case 2

In this second trial use case, a battery is added to the biogas assets and the wind farms in the simulation. Both the negative and positive balancing of the wind portfolio is now possible.

Furthermore, historical spot prices are included since the objective is to obtain revenue on the spot market as well.

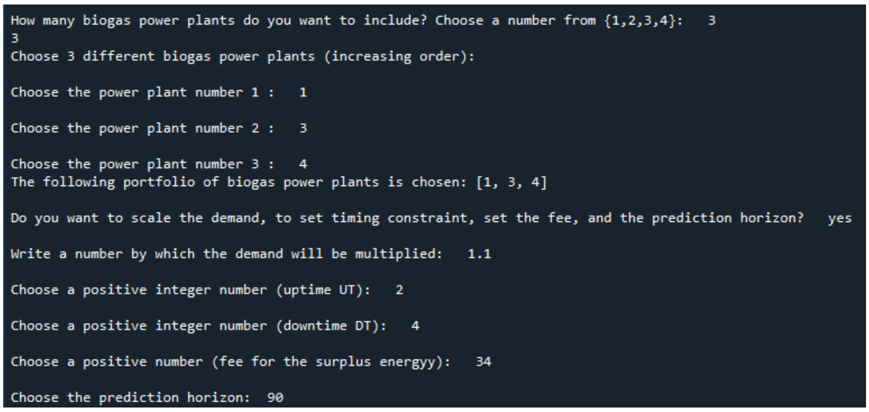
The set of parameters, for trial use case 2, presented here is also shown in Figure 7 and Figure 8 which illustrate the entry of the use case parameters into the trial system interface:

- Chosen period: 15 consecutive days;
- *Capacity*, *Pmax*, and *Fuel Inflow* parameters were modified;
- Inclusion of following assets:
  - Two wind farms: 1 and 4,
  - The battery,
  - Three biogas power plants: 1, 3, and 4;
- The imbalance was multiplied by 1.1;
- Timing constraints were included: *uptime* (minimum “on time”) = 2 hours, and *downtime* (minimum “off time”) = 4 hours for all the turbines;
- The fee for the surplus energy (*f*) was chosen to be 34 Euros/MWh;
- The prediction horizon was set to 90 hours.



```
Do you want to choose the last available date and the length of the history?   y

How many days before now? zero means 'now':   0

History's length':   30

Do you need the corresponding history?':  y

How many wind parks do you want to include? Choose a number from {1,2,3,4}:   2
2
Choose 2 different wind parks (increasing order):

Choose the wind park number 1 :   1

Choose the wind park number 2 :   2
Downloading Wind park forecasts and actuals: ['Park1', 'Park2']
Downloading Park1
Downloading Park2
Downloading commercial spot price forecast from https://awb.dev.ds.alpiq.io/PC/106317213
Downloading spot price actuals from https://awb.dev.ds.alpiq.io/NC/DE.EEX/Index

Do you want to modify Pmax, Fuel_Inflow, and Capacity?   y

Multiply all capacities   by this number:   1

Multiply all Pmaxes       by this number:   2

Multiply all fuel inflows by this number:   1

Multiply battery's cap    by this number:   1

Multiply battery's Pmax   by this number:   2
All the capacities   will be multiplied by 1.0
All the Pmaxes       will be multiplied by 2.0
All the fuel inflows will be multiplied by 1.0

Do you want to include the battery?   y
You have chosen to include the battery
```

Figure 7 – Second trial use case as shown in the software (Part I)



```
How many biogas power plants do you want to include? Choose a number from {1,2,3,4}:   3
3
Choose 3 different biogas power plants (increasing order):

Choose the power plant number 1 :   1

Choose the power plant number 2 :   3

Choose the power plant number 3 :   4
The following portfolio of biogas power plants is chosen: [1, 3, 4]

Do you want to scale the demand, to set timing constraint, set the fee, and the prediction horizon?   yes

Write a number by which the demand will be multiplied:   1.1

Choose a positive integer number (uptime UT):   2

Choose a positive integer number (downtime DT):   4

Choose a positive number (fee for the surplus energyy):   34

Choose the prediction horizon:  90
```

Figure 8 – Second trial use case as shown in the software (Part II)

4.4.1 Historical trading schedules used to trial use case 2

For this study, in order to carry out back-testing on use case 2, historical trades conducted by ALPQ's traders for two biogas-fired power plants (Biogas 1 and Biogas 2 ([1,2])) were obtained. These trades were conducted on the DA market of EPEX SPOT, and the power plants were managed separately, i.e., these schedules determine the *independent profits* achieved by ALPQ's traders. The trading decisions were conducted through a market order and the calculations were conducted within the optimisation procedure. The historical trades were conducted in the period January-September 2021.

There are two more biogas assets ([3,4]), but they have been managed since January of 2022 and the data was insufficient at the time of this study to obtain historical schedules.

Using data from January-September 2021 and from March-April 2022, the profits, for both *independent profits* (the “benchmark”) and for the *default task* (the historical imbalance handled with the usage of the battery) are simulated, with a set of parameters to be varied; these include:

- *Pmax*: maximum production output of the turbines;
- *Capacity*: capacity of biogas assets;
- *Pmax Battery*: maximum production output of the battery;
- *Fuel Inflow*: fuel required for the production of the biogas plants;
- *RelRevenue*: relative revenue (compared with that of when no balancing nor edgeFLEX algorithms are applied).

4.5 Conclusion on the VPP optimisation software and inputs

The management of the assets is conducted by flexible software where the user can define which wind farms to manage, which assets to involve, and what time periods to use. A key element in the development of this optimisation software and its user interface, is the consideration of its appropriate integration and connection to the edgeFLEX platform.

The same algorithm as for the VPP optimisation work (Deliverables 3.2 and 3.3) is deployed using the software for the trial simulations presented in this report. When carrying out the trial simulations, specific inputs were defined for two representative use cases, including different setups of VPPs and historical trade schedules, to back-test the VPP optimisation algorithm.

The software has been developed so that it can accommodate as many modelled assets (i.e., biogas units and batteries) as desired and as many uncontrollable assets (i.e., wind farms) as desired, by entering their configurations.

Two use cases are trialled in the simulations. In the first use case, the biogas plants are included, which means that only the negative balancing of the wind portfolio is possible. In the second use case, a battery is added on top. Both the negative and positive balancing of the wind portfolio is therefore possible; in addition, the objective of earning revenue on the spot market is added to this use case.

5. Results of the trials of the two use cases

In this section, the results of the trial simulations are presented; the output of the simulations carried out with the two selected use cases are provided.

Then, the impact of the use of a range of historical trading schedules on the profit generated, as well as the impact generated by the use of different parameters for the configuration of the VPP is presented.

In the following part, a sensitivity analysis of the optimisations is provided which compares how the target variable of profit varies in response to modifications of the other input parameters of the trial.

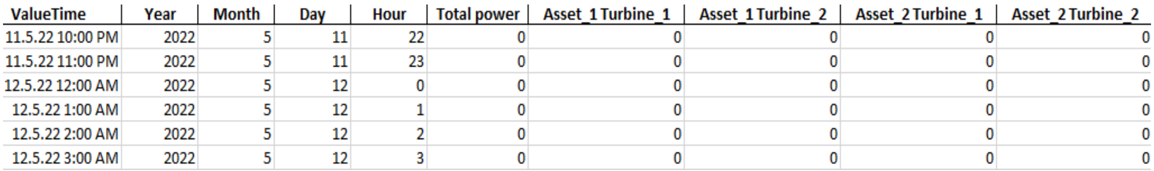
Finally, the effects of increasing the VPP portfolio size are described.

5.1 The results of the trial of use case 1

In this first use case, only the biogas-fired plants and wind farms are included in the simulation, meaning that only the negative balancing of the wind portfolio is performed.

Figure 9 shows the output file for the chosen inputs. This is related to the first use case, where only the biogas assets are included and compensate for the wind farm’s negative imbalance.

The first 5 columns relate to the time; *Total power* represents the total power output of all the turbines and contains the normalised total power output; the last 4 columns show the power production of each turbine. In the default settings, historical prices are not included. In this case, the battery was not included.



ValueTime	Year	Month	Day	Hour	Total power	Asset_1 Turbine_1	Asset_1 Turbine_2	Asset_2 Turbine_1	Asset_2 Turbine_2
11.5.22 10:00 PM	2022	5	11	22	0	0	0	0	0
11.5.22 11:00 PM	2022	5	11	23	0	0	0	0	0
12.5.22 12:00 AM	2022	5	12	0	0	0	0	0	0
12.5.22 1:00 AM	2022	5	12	1	0	0	0	0	0
12.5.22 2:00 AM	2022	5	12	2	0	0	0	0	0
12.5.22 3:00 AM	2022	5	12	3	0	0	0	0	0

Figure 9 – An example of an output of the MPC optimisation

Figure 10 shows the production schedule of the biogas power plant. It shows that the biogas asset is producing electricity whenever there is a negative imbalance of the wind farms (i.e., when the wind farms produce less than what was forecasted). Biogas plants can be used to compensate imbalance of wind farms and/or to make revenue on the spot market (DA market). When the normalised production is of 1, it means the imbalance is bigger or equal than the whole capacity of the biogas plants.

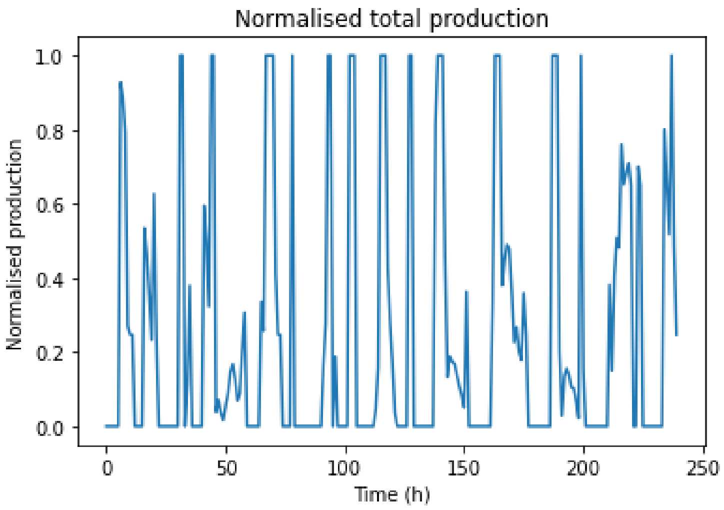


Figure 10 – Normalised total production time series

5.2 The results of the trial of use case 2

In this second use case, a battery is added to the biogas plants and wind forms used in the trial. The compensation of the imbalance is both negative and positive, and an extra objective is added to obtain revenue on the spot market.

Figure 11 and Figure 12 show respectively the total power output of the biogas power plants and the discharge of the battery. These variables are normalised and are displayed against prices, which is represented by the second y-axis. In these figures, one can observe that the high production and discharge occur when the spot price is high.

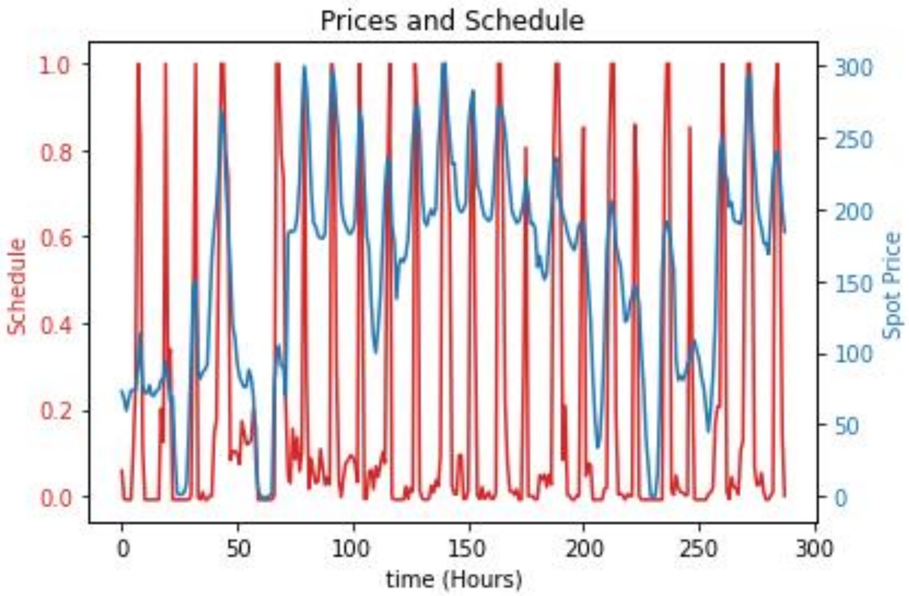


Figure 11 – The total power output of all the biogas fired power plants

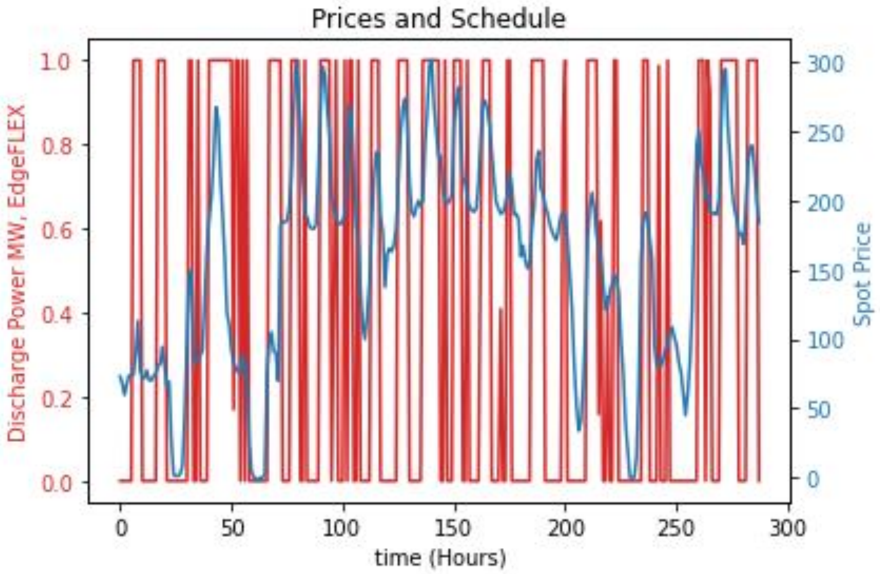


Figure 12 – The normalised discharge schedule of the battery vs normalised spot prices

The charge should happen when the price is low; even better is when the price is negative. Therefore, in Figure 13, the price is multiplied by (-1), and it is the second axis, and in this figure the picture is similar.

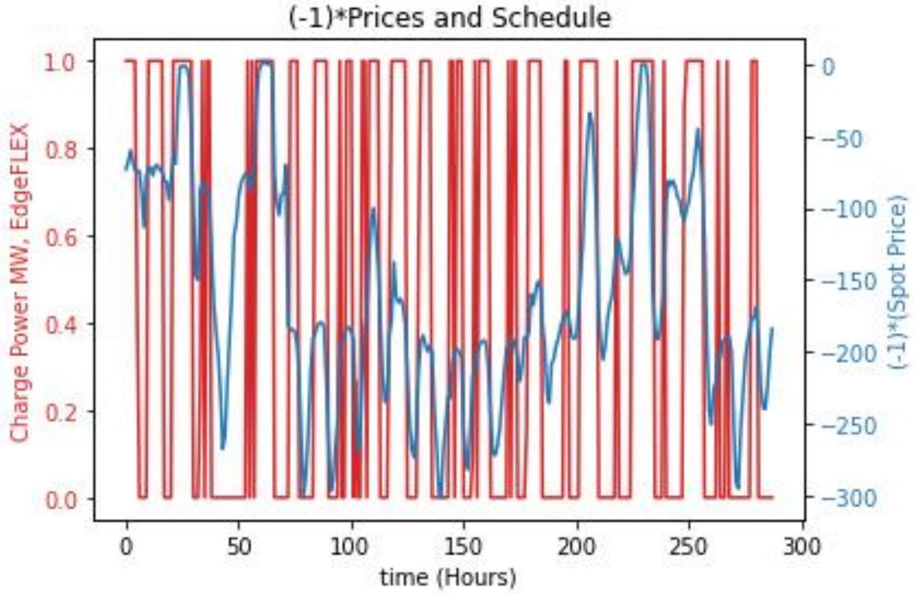
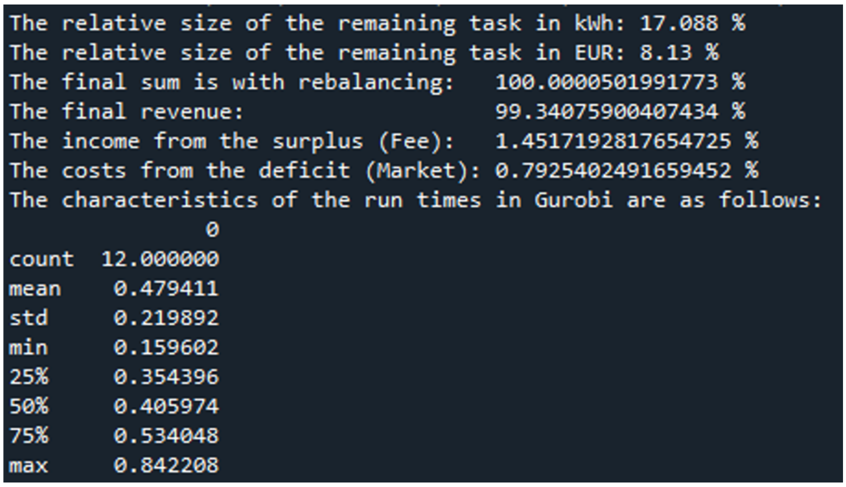


Figure 13 – The normalised charge schedule of the battery vs normalised spot prices multiplied by (-1)

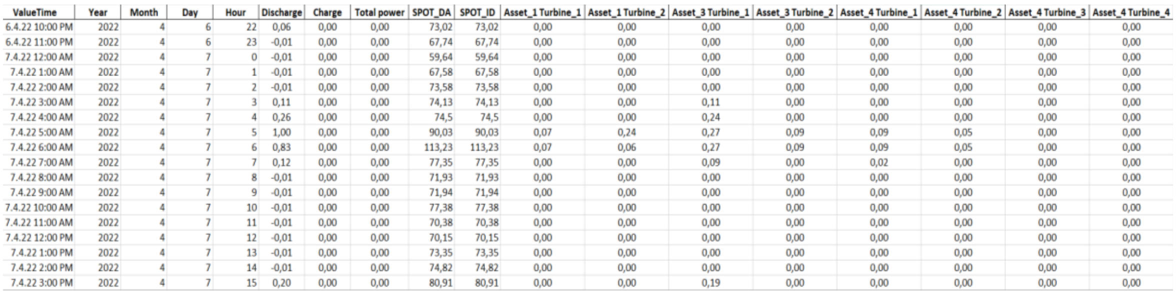
Figure 14 shows the output of the program running the parameters of use case 2. In this figure, the profits in Euros were normalised due to commercial confidentiality issues. However, it can be said that these values are in the order of magnitude of hundreds of thousands of Euros.



```
The relative size of the remaining task in kWh: 17.088 %
The relative size of the remaining task in EUR: 8.13 %
The final sum is with rebalancing:    100.0000501991773 %
The final revenue:                    99.34075900407434 %
The income from the surplus (Fee):    1.4517192817654725 %
The costs from the deficit (Market): 0.7925402491659452 %
The characteristics of the run times in Gurobi are as follows:
               0
count  12.000000
mean    0.479411
std     0.219892
min     0.159602
25%     0.354396
50%     0.405974
75%     0.534048
max     0.842208
```

Figure 14 – The normalised output of the program

Figure 15 shows the output file of the program. Note that here as well the power output is normalised. It is also to be noted that Figure 9 and Figure 15 are the tables generated by the program. However, Figure 15 contains more columns because historical prices are included; the battery is included, and there are more columns related to the turbines since Biogas 4 contains four turbines.



ValueTime	Year	Month	Day	Hour	Discharge	Charge	Total power	SPOT_DA	SPOT_ID	Asset_1 Turbine_1	Asset_1 Turbine_2	Asset_3 Turbine_1	Asset_3 Turbine_2	Asset_4 Turbine_1	Asset_4 Turbine_2	Asset_4 Turbine_3	Asset_4 Turbine_4
6.4.22 10:00 PM	2022	4	6	22	0,06	0,00	0,00	73,02	73,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
6.4.22 11:00 PM	2022	4	6	23	-0,01	0,00	0,00	67,74	67,74	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 12:00 AM	2022	4	7	0	-0,01	0,00	0,00	59,64	59,64	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 1:00 AM	2022	4	7	1	-0,01	0,00	0,00	67,58	67,58	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 2:00 AM	2022	4	7	2	-0,01	0,00	0,00	73,58	73,58	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 3:00 AM	2022	4	7	3	0,11	0,00	0,00	74,13	74,13	0,00	0,00	0,11	0,00	0,00	0,00	0,00	0,00
7.4.22 4:00 AM	2022	4	7	4	0,26	0,00	0,00	74,5	74,5	0,00	0,00	0,24	0,00	0,00	0,00	0,00	0,00
7.4.22 5:00 AM	2022	4	7	5	1,00	0,00	0,00	90,03	90,03	0,07	0,24	0,27	0,09	0,09	0,05	0,00	0,00
7.4.22 6:00 AM	2022	4	7	6	0,83	0,00	0,00	113,23	113,23	0,07	0,06	0,27	0,09	0,09	0,05	0,00	0,00
7.4.22 7:00 AM	2022	4	7	7	0,12	0,00	0,00	77,35	77,35	0,00	0,00	0,09	0,00	0,02	0,00	0,00	0,00
7.4.22 8:00 AM	2022	4	7	8	-0,01	0,00	0,00	71,93	71,93	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 9:00 AM	2022	4	7	9	-0,01	0,00	0,00	71,94	71,94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 10:00 AM	2022	4	7	10	-0,01	0,00	0,00	77,38	77,38	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 11:00 AM	2022	4	7	11	-0,01	0,00	0,00	70,38	70,38	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 12:00 PM	2022	4	7	12	-0,01	0,00	0,00	70,15	70,15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 1:00 PM	2022	4	7	13	-0,01	0,00	0,00	73,35	73,35	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 2:00 PM	2022	4	7	14	-0,01	0,00	0,00	74,82	74,82	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7.4.22 3:00 PM	2022	4	7	15	0,20	0,00	0,00	80,91	80,91	0,00	0,00	0,19	0,00	0,00	0,00	0,00	0,00

Figure 15 – The normalisation of the output file: produced and consumed power are normalised

5.3 The use of historical trading schedules in use case 2

For this study, in order to carry out back-testing, historical trades conducted by ALPQ's traders for two biogas-fired power plants (Biogas 1 and Biogas 2 ([1,2])) were obtained. These trades were conducted on the DA market of EPEX SPOT, and the power plants were managed separately, i.e., these schedules determine the *independent profits* achieved by ALPQ's traders. The trading decisions were conducted through a market order and the calculations were conducted within the optimisation procedure. The historical trades were conducted in the period January-September 2021.

Optimal comparisons can be conducted by the independent management of the biogas power plants by comparing the independent profits they generate. This is implemented as MPC.

The real trading outcome in Euros is not disclosed due to issues of commercial confidentiality and this information provided is therefore normalised: the independent profit of the algorithm is denoted as *Rev*, and the revenue under specific inputs is denoted as *Revenue(inputs)*. The parameter of interest is as follows:

$$\mathrm{RelRevenue}(inputs) = 100 \times \frac{Revenue(inputs)}{Rev}\%$$

The value of *RelRevenue(inputs)* indicates how the revenue from the sale of power by the biogas power plants is affected by the necessity to perform balancing.

For example:

- $\mathrm{RelRevenue}(\text{No balancing task \& edgeFLEX algorithms}) \quad = 100\%$
- $\mathrm{RelRevenue}(\text{No balancing task \& historical schedules}) \quad = 98.09\%$
- $\mathrm{RelRevenue}(\text{Balancing task \& battery \& edgeFLEX algorithms}) \quad = 100.3\%$ (f = 36)
- $\mathrm{RelRevenue}(\text{Balancing task \& no battery \& edgeFLEX algorithms}) \quad = -23.82\%$

Compared with the scenario where no balancing is required, and historical schedules are used, an improvement of about 2% in revenue is modelled when biogas assets alone generate revenue on the spot market (first line). When a battery is added (third line), i.e., corresponding to trial use case 2, the difference revenue is even slightly higher. However, when the balancing task exists but there are no assets to balance in both direction (fourth line), the surplus of the energy has to be sold and cannot be stored and dispatched when higher prices are available – this is what explains the negative relative revenue.

Figure 16 demonstrates the values of *RelRevenue* for the following cases:

- Systems with the battery (blue line);
- System without the battery (orange line).

In Figure 16, the x-axis indicates what number multiplied the imbalance in Equation (15). The left part of the figure visualises the entire scale of *RelRevenue* and the vertical line at point x=1 show the default values: if the battery is included then the independent profit of this system is by 13.06% higher than that of a system without the battery. All the profits in Figure 16 are divided by the independent profit of the system with two biogas power plants and the battery (*Rev*). The historical imbalance imposes costs of balancing the deficit and enables to earn by exploiting the surplus. The unbalanced surplus energy (i.e., what remains after charging the battery) is sold for 36 Euros/MWh. This value is strictly below the median (64 Euros/MWh) and the mean (62 Euros/MWh).

The difference between the revenue and cost for the historical imbalance for the system without the battery is negative: in this case, *RelRevenue* is -15.04%. However, if a battery is included for this system, then *RelRevenue* is 100.3%. This case is shown on the right side of Figure 16, with the vertical line that passes through point x=1. The right part of the figure shows *RelRevenue* in more detail. For instance, it is possible to observe that the maximum *RelRevenue* is around x=0.5 and at this point *RelRevenue* is 119.72%.

The dependence of profits with regards to the multiplier of the imbalance resembles an inverted U-curve as is shown in the right part of Figure 16. The increase in imbalance leads to a growth in revenues from the sale of the surplus, but the costs associated with the deficit increase; in addition, the revenues of the flexible assets also decrease if the imbalance burden increases.

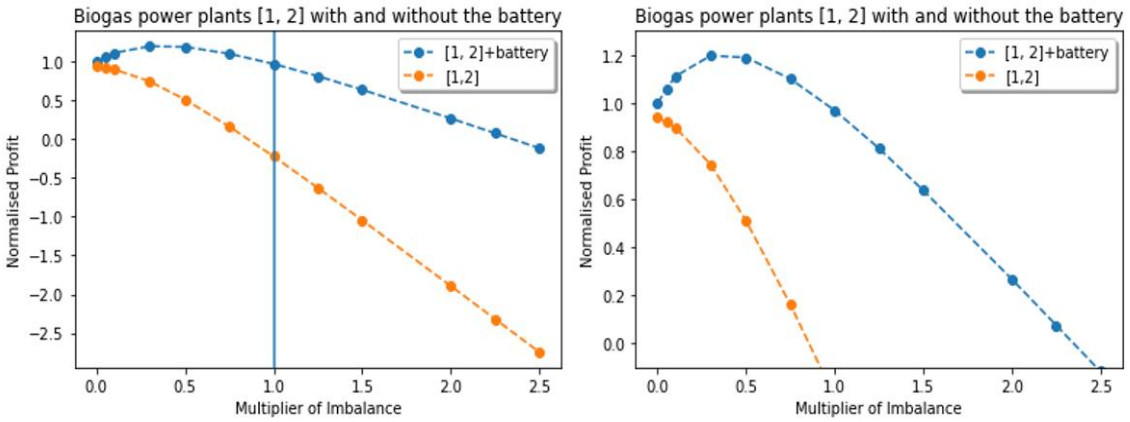


Figure 16 – Normalised profit: dependence on the multiplier of the imbalance

Figure 17 shows the percentage of the deficit covered with [1, 2] with and without the battery. At point 1 (x=1, default imbalance), the system with the battery covers 53.45% of the deficit; without the battery, this coverage is of 40.36%. The more imbalance is covered, the smaller the deficit costs: biogas plants provide capacity for the deficit; the battery does this too, but it can also be recharged with the excess energy.

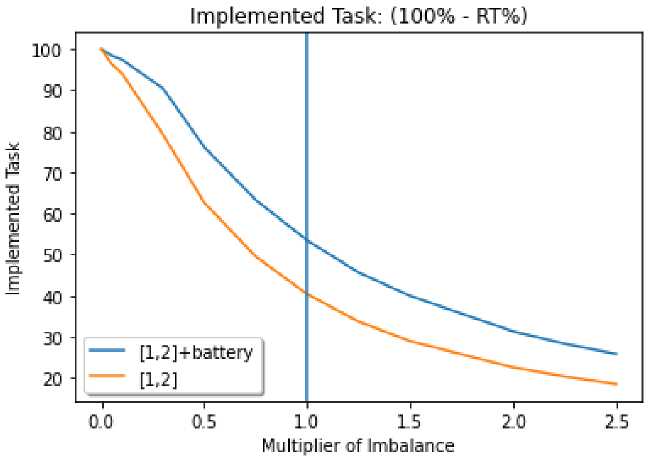


Figure 17 – Performed Task (covered deficit)

Figure 18 shows *RelRevenue* for other sets of assets: in all the cases, there is a battery and in all the cases, the profits are divided by the value of the corresponding *independent profit*. In the left part of Figure 15, the unbalanced surplus energy is sold for 20 Euros/MWh (f = 20 Euros/MWh); in the right part of Figure 15, this price is 36 Euros/MWh. There are three inverted U-curves: e.g., for a single asset ([2]), this curve is thin, but its maximum is the largest: *RelRevenue* can be 132.45% of the independent profit (f = 36 Euros/MWh), however, the rise in the imbalance may substantially decrease the profit. For the system with four assets, this U-shape is the broadest: the maximum *RelRevenue* is below 120% (f = 36 Euros/MWh), but the profit is less vulnerable to the increases in the imbalance size. The altitude (height) of the inverted U-curve determines the maximum profitability from the size of the imbalance. The width of the U-curve determines the robustness of the profits to the increase in the number of the balanced assets, or the balancing task.

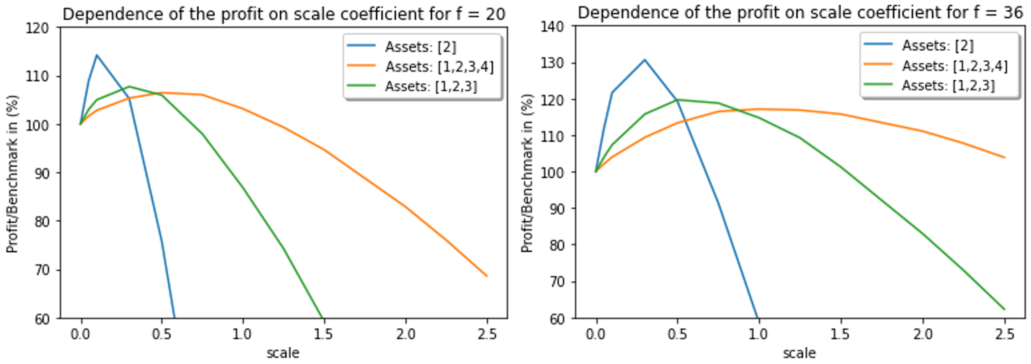


Figure 18 – The dependence of the profits on the size of the imbalance when the vector of imbalances is multiplied by a constant number (x-axis)

Figure 19 clarifies the notions of the width and altitude of the inverted U-curve. The left part of the figure indicates the altitude of the blue and orange U-curves. The middle part indicates the width of the orange U-curve. The right part demonstrates points on the U-curve when it is reasonable to increase the imbalance (point 1); decrease the imbalance (point 3); to preserve the amount of the imbalance (point 2).

The ratio of "*spot & balancing*" (i.e., trial use case 2) over benchmark is larger for three assets than this same ratio for one asset; note that the absolute profit for three assets is higher than for one asset.

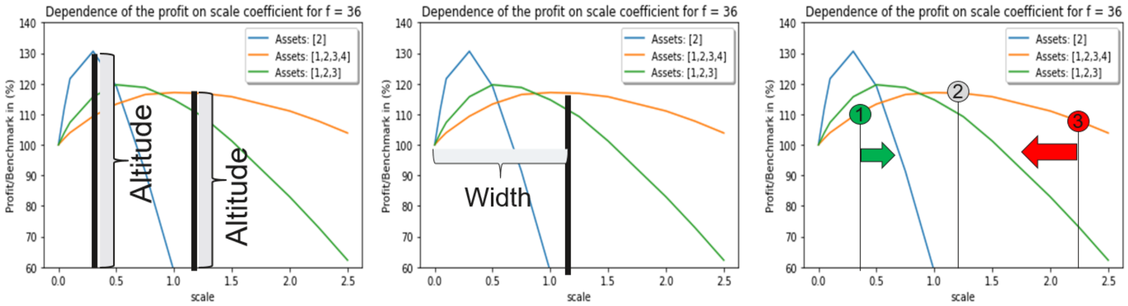


Figure 19 – The width and altitude of the U-curves

5.4 Sensitivity analysis of profits based on variations in trial use case parameters

In this section, the result of varying certain key use case parameter on the profits generated is presented.

The biogas power plants in use case 1 balance four large wind farms. Sometimes, the capacity of the VPP is insufficient to provide balancing. This missing energy must be bought on the market. We denote this missing energy as the *remaining task*, and the deficit is the biggest concern for the balancing assets since it has to be compensated at market price.

Figure 20 shows the initial task (blue line) and the remaining task for assets [1, 2] on the left and for assets [1,2,3,4] on the right. The addition of new biogas power plants to the pool of balancing assets increases its balancing capacity for the deficit as it is demonstrated in this figure.

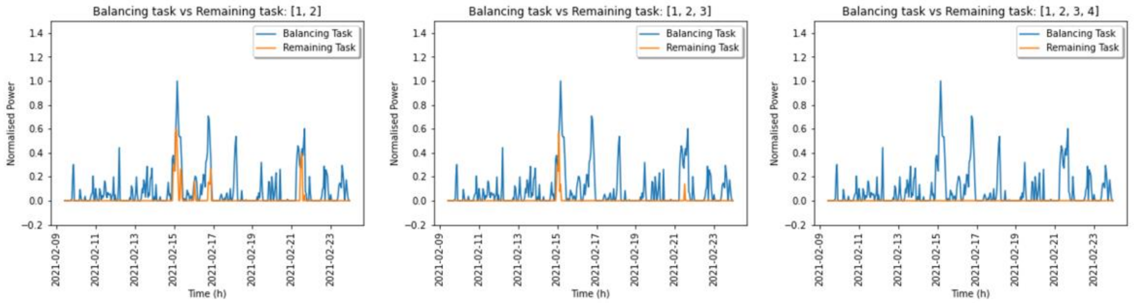


Figure 20 – The balancing task and the remaining task (deficit), with two assets [1, 2] on the left; three assets [1,2,3] in the middle; all four assets [1,2,3,4] on the right.

Table 4 demonstrates how the profit reacts to the varying parameter values of the assets.

In Table 4, the considered data period is January-September 2021. The column *Benchmark vs parameters* indicates respectively the *independent profits* (*IP*) and the default task (*DTa*) i.e., the historical imbalance handled with the usage of the battery.

If a parameter e.g., *Pmax* (maximum production of the biogas plant), is multiplied with a number, it means that in the *Pmax* of all the turbines is multiplied by this number.

The table suggests that the factor which affects profit the most is fuel inflow, which is expected. Less straightforward is the fact that the doubling of *Pmax* would increase the profit substantially more than the doubling of the size of the storage facility (*Capacity*); however, it is to be considered that the doubling of the size of the storage facility might require more investments. Doubling the capacity as well as the maximum production of the battery (*Pmax battery*) leads to higher revenue increases than compared with the doubling of the capacity on its own.

Some elements feeding into the investment decision for turbines or storage facilities could be based on this sensitivity analysis.

Table 4 – Sensitivity of profit on Pmax, capacities, and fuel inflow (valid for back-testing period: January-September 2021)

Benchmark (IP) vs parameters (DTa)	Pmax	Capacity	Capacity & Pmax Battery	Fuel Inflow	RelRevenue
IP	1	1	1	1	100%
DTa	1	1	1	1	106.25%
IP	**2**	1	1	1	104.27%
DTa	**2**	1	1	1	110.74%
IP	1	**2**	1	1	101.71%
DTa	1	**2**	1	1	108.14%
IP	1	1	**2**	1	106.13%
DTa	1	1	**2**	1	128.59%
IP	1	1	1	**2**	179.35%
DTa	1	1	1	**2**	208.16%

Following the optimisation problem formulation (Equation (16)), we define the following output characteristics of the period of VPP operation:

$$\text{Remaining Task (deficit in kWh)\%} = 100 \times \frac{\sum_{t=1}^{N} z_t^d}{\sum_{t=1}^{N} IB_t^+}\%$$

$$\text{Remaining Task (deficit in Euros)\%} = 100 \times \frac{\sum_{t=1}^{N} z_t^d \cdot Spot_t}{\sum_{t=1}^{N} IB_t^+ \cdot Spot_t}\%$$

Note that the *Remaining Task (deficit % in Euros)* determines the costs associated with the inability to cover the deficit. This is related to the situation where the capacity of the VPP is insufficient to provide balancing. This missing energy must be bought on the market. This deficit is the biggest concern for the balancing assets since it has to be compensated at market price.

Figure 21 demonstrates the values of *Remaining task* both in deficit % in kWh and Euros, for different multiplying coefficients of *Pmax*, for the period March-April 2022. On the left side of the figure, multiplying coefficients of *Pmax* from 0.1 to 1 are shown; on the right side, there are *Pmax* coefficients from 1 to 20.

When the coefficient is below the unit value, both *Pmin* and *Pmax* are multiplied by this value and *Pmin* is half the value of *Pmax*. However, if the multiplier is above the unit value, then only *Pmax* is multiplied by the multiplier. There is a fixed number of assets in the figure for which only *Pmax* of the biogas plants is changing.

Remaining Task (deficit % in kWh) is always bigger than *Remaining Task (deficit % in Euros)* and this is given by the optimisation: when the capacity is not sufficient to cover the deficit, the optimisation procedure will ensure that it will happen at times when the price is low.

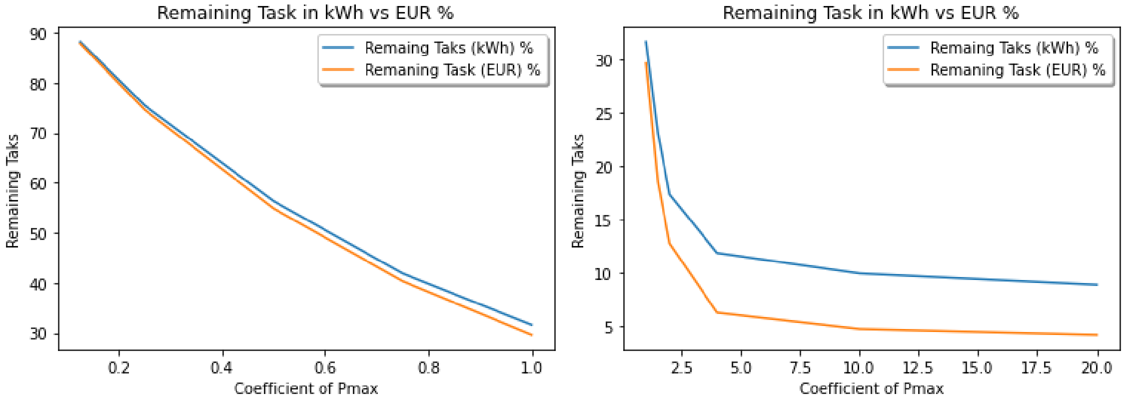


Figure 21 – The dependence of *Remaining Task* on the value of *Pmax*

Table 5 indicates the values of *Remaining Task (deficit % in kWh)* and *Remaining Task (deficit % in Euros)* for different sets of biogas assets without a battery (for March-April 2022). For example, for assets [1,2,3,4], *Remaining Task (deficit % in Euros)* is more than 10 times smaller than *Remaining Task (deficit % in kWh)*.

Table 5 – Portfolios of assets without a battery

Assets	Remaining Task (deficit % in kWh)	Remaining Task (deficit % in Euros)
[1,2]	22.63%	16.57%
[1,2,3,4]	4.247%	0.413%
[1,2,3]	12.61%	6.851%
[1,3,4]	4.888%	0.894%
[2,3,4]	5.091%	1.057%
[1]	42.82%	37.08%
[2]	50.61%	45.56%
[3]	43.44%	37.65%
[4]	11.82%	7.129%

Table 6 shows how the profits are affected by the downtime (DT) and uptime (UT) of the biogas turbines. The table indicates that these timing constraints can decrease the profits by more than five percent. Thus, the investments into the turbines with lower uptimes and downtimes can lead to better incomes.

Table 6 – Sensitivity to profit to timing constraints of the biogas-fired power plants

DT	UT	Assets	RelRevenue
0	0	[1,2,3,4]	100%
4	4	[1,2,3,4]	99.82%
12	12	[1,2,3,4]	95.45%
0	0	[2,3,4]	82.53%
12	12	[2,3,4]	78.32%
0	0	[1]	16.75%
12	12	[1]	16.53%
0	0	[2]	12.83%
12	12	[2]	11.64%
0	0	[3]	16.92%
12	12	[3]	15.54%
0	0	[4]	50.63%
4	4	[4]	50.56%
12	12	[4]	48.22%

Figure 22 shows how profits and revenues depend on the prediction horizon within the MPC framework. The profit could be increased by 4.3% by increasing the prediction horizon from 48 hours ahead to 80 hours ahead. This could be a cheaper way to increase profits and is dependent only on the software parameters. On the other hand, the increase in *Pmax* or *Capacity* requires more substantial investments.

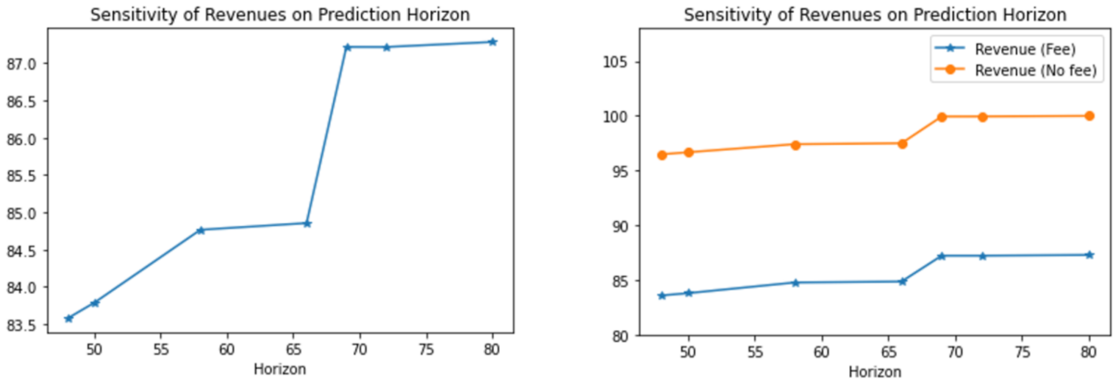


Figure 22 – Sensitivities of profits and revenues to prediction horizon

5.5 The effects of increases in the size of the portfolio of the managed assets in the VPP

In Section 5.2, the notion of the inverted U-curve was introduced. Figure 23 demonstrates the inverted U-curves for different settlement prices, *f*, of the unbalanced energy (for period January-September 2021). The higher the value of *f*, the more desirable is the shape of the inverted U-curve, but the less realistic it is to find a buyer of this energy. However, if the price is reasonable, the operator may carry out the sale of this energy on the market and the difference between the market price and the reasonable *f* can be used for the operation costs of the VPP and investments decisions.

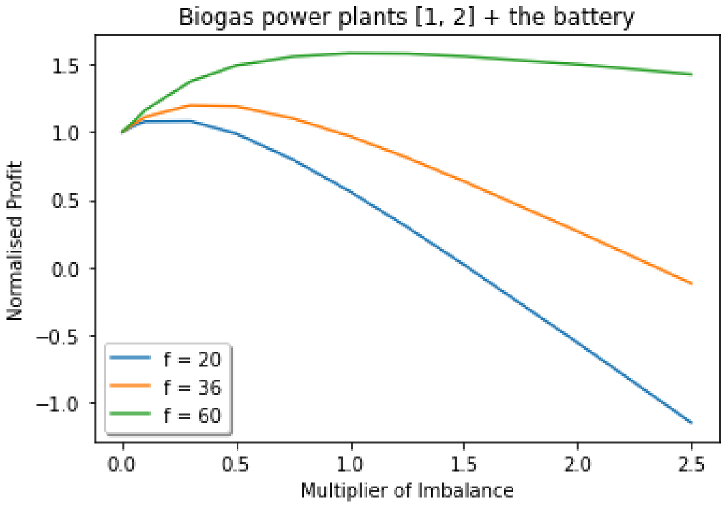


Figure 23 – Inverted U-curves for different values of f

Having chosen the value of *f*, (e.g., *f* = 20 Euros/MWh or *f* = 36 Euros/MWh), the operator shall reach a decision on the growth of the system, which can be twofold:

- The increase in the number of the balanced RES assets;
- The increase of the balancing assets in the VPP.

When making decisions about the increase in the number of balanced RES assets, the inverted U shape of profits should be respected. A reasonable increase in the number of the balanced assets can substantially increase the profit, but large increases may substantially decrease the profit. This all depends on the altitude and the width of the inverted U-curve.

The inclusion of the biogas assets reduces the costs associated with deficit, increases the revenue of the other biogas assets, but it reduces the distributed share of the surplus energy. The inclusion of a biogas asset increases the width of the inverted U shape, but it reduces its altitude. Therefore, as in the case of the RES assets, the inclusion of the biogas power plants is a question of a compromise. On the other hand, the inclusion of the battery increases both the altitude and the width of the inverted U-curve, and it is desirable by all the parties: the RES asset owners, the biogas power plants' owners, batteries' owners, and the operator.

In Section 6.3, more consideration is given to how these profits can be used for investments and how the regulators should approach such systems.

5.6 Conclusions on the results and sensitivities

In this section, it has been shown through the usage of historical trading schedules for the back-testing, that that the optimisation model is effective and can be applied to real transactions.

In the first trial use case, with the biogas plants solely compensating the negative imbalance of the wind farms, the imbalance is only partially offset (in one direction). If prosumer assets, such as batteries, i.e., in the second trial use case, are added, this imbalance can be offset in both directions (positive as well).

The profit optimisation of the VPP setup, of which the back-testing is simulated and presented in this deliverable, shows that an improvement of 2% in profit could be achieved when the biogas assets and a battery balance the wind farm production. It is also important to note that whilst the inclusion of further biogas assets is not positively correlated with profit, the addition of further batteries is.

Through the back-testing, it has been shown that the optimisation software can be used in two modes: for the asset owner to balance their portfolio and reduce the imbalance costs (and to help the grid to be balanced), as well as generate revenue in spot markets.

6. Implications of this field trial for 5G, grid support and regulatory frameworks

This section considers the nuances of the field trials by taking into consideration aspects linked to 5G, the relation to the grid and regulations.

6.1 5G support for VPP optimisation

Today, algorithms for optimisation of the financial results of the VPP asset owners exist. The work carried out in the frame of the VPP optimisation and subsequent testing, or trial, may be used to improve existing solutions. The goal is to save VPP owner costs, e.g., by charging batteries when there is wind, or when lower energy prices, or demand for the usage of wind turbines, is lower. Currently, energy distribution and dispatch are planned in intervals of 1 hour. VPP optimisation solution will shorten this interval to 15 minutes, making it compatible with the ID market. It can be expected that VPP asset owners will only accept this solution if it decreases their costs by at least 1%, threshold under which it may not be valuable to invest efforts into the new solution's implementation.

The optimisation algorithm could be deployed within commercial power networks in the coming 3-5 years during which VPP facilities will require improvements in communications networks to communicate with VPP assets. 4G or 5G networks could be used to provide such communications to VPP assets.

In the longer term, clouds located close to each facility (wind farm) are likely to be required to provide the computational power and data storage required to support the monitoring and control of VPP assets. By that time, facilities under VPP management will include ever smaller production assets. Indeed, in the future, an asset could be e.g., a residential battery, a refrigerator in a restaurant. It is foreseen that a big shift from the management of big facilities by VPPs to the management of many much smaller facilities will occur. 5G Edge Infrastructure can provide the communications as well as edge computational and storage infrastructure required to fulfil these longer-term requirements of optimised VPPs.

The 5G communications services which can support VPP operations and their relation to VPP operations are defined in Table 7 below. Those 5G services are described in Deliverable 3.1 and in Deliverable 6.2 in more detail.

Table 7 – VPP related services and 5G solutions

Service 5G solution	VPP Automated Generation Control	VPP Optimisation	Advanced Flexibility Trading
Private Networks	✓	✓	✓
Hybrid Networks	✓	✓	✓
Mission Critical Networks	✓	✓	✓
Mobile Networks for Massive IoT Communications	✓	✓	✓
Edge Cloud	-	✓	✓
Central Cloud	✓	✓	✓
5G Device Management API	✓	✓	✓
URLLC	-	-	-
Network Slicing	✓	✓	✓
eSIM	✓	✓	✓

Energy market actors will likely not be impacted in a direct manner by the optimisation service. However, the service will influence the energy market indirectly by improving the efficiency of VPP operators, i.e., by increasing the income generated by the assets under management.

6.2 Considerations regarding the grid and flexibility trading as an Energy Community

The portfolio of assets considered in this case study is small. However, this study emphasises the potential to scale portfolios in terms of the flexible assets and DERs. The logic applied in this case study can be applied to larger sets of assets and hence be used in the grid as a contribution to grid balancing. That is why aspects such as the scaling of computations as well as the profitability yielded by new turbines in the wind farms or new flexible assets in the VPP are addressed. It is to be noted that, whilst neither the gradual increase nor other decomposition methods have been used in these deliverables (brute force was used instead), it is recommended to resort to decomposition methods for larger pools of assets. Proper management of the inverted U-curves can lead to the following feature:

$$\frac{\partial \text{ size\_of\_VPP}}{\partial t} > 0$$

A large enough VPP should be first integrated into an energy community, and then it can become part of the grid, contributing to grid balancing. Following this, these VPPs can provide their balancing services to the market, or they can offer the owners of the relevant flexible assets membership in their VPP if they satisfy a defined set of criteria.

6.3 The VPP optimisation creates a need for regulatory adaptations

As is noted in Section 3.9.5, if the real settlements for the unbalanced energy are included in the objective, then the optimisation procedure will push the value of z_t^s, which is counter to the goal of balancing. It should be possible to profit from the unbalanced surplus energy only if all measures to prevent this unbalance were taken prior to this. Otherwise, too much of the unbalanced energy will flow to the grid. Figure 4 demonstrates the proposed scheme in which the operator's revenue is proportional to the metric of the satisfaction of the imbalance in both directions. The same operator sets the parameters of the optimisation. Apart from these parameters, the regulator can control other elements. A proposal in three parts into to which the surplus can be divided:

Sale of surplus = [Assets' settlements] + [Operation costs of VPP] + [Investments RES&Flex]

It is reasonable to assume that the profits from the assets added by *Assets' settlements* exceeds the sum of *independent profits*. The protection of this feature should be ensured by the regulator, since otherwise the asset owners might wish to disconnect from the VPP.

As for the part *Operation costs of VPP*, the regulator should verify that the management's income is proportional to the relevant metrics of the satisfaction of the imbalance. The regulators have to ensure relevant methods of the wind production forecast are employed. Part of *Operation costs of VPP* should be used for the placement of sensors to the wind production units in order to improve the quality of the data, and hence improve the forecasting quality.

The amounts that remain after the settlements of the assets and operation costs should be spent on investments into the flexible assets in the VPP and into RES assets that would be connected to the VPP. The investments can be as follows:

- Purchase, production or leasing of power turbines with larger *Pmax* and lower uptime and downtime;
- Purchase, production or leasing of wind turbines;
- Purchase of storage facilities;
- Predictive maintenance of the turbines;

- Logistics of the deliveries of renewable fuels;
- Process of biogas production;
- Optimisation software.

6.4 Conclusion on the implication of the field trials for 5G, grid support and regulatory frameworks

Given the change in the energy mix and the addition of a substantial number of small-scale assets, a shift from the classic management of big facilities by VPPs to the management of many much smaller plants is expected. The 5G Edge Infrastructure can provide not only the communications and edge computational but also the storage infrastructure required to fulfil these longer-term requirements of optimised VPPs.

Furthermore, given the large number of assets which can be potentially managed and optimised under the optimisation software, this makes it possible for Energy Communities, with many small DER assets, to make use of the work presented here.

It is also important to stress that the regulatory bodies will have to ensure relevant adaptations in line with VPP optimisation.

7. Conclusions of the optimisation research and trials

In this study, we have described the testing of the novel VPP optimisation as well as demonstrated the profitability of these enhanced VPP systems and their scaling potential for growth. The optimisation problem itself is computationally complex and mixed integer optimisation algorithms have to be applied. While it is possible to rely on the capabilities of the solver for the system in question (four biogas power plants and one battery), for a system with a large number of assets, it is necessary to rely on decomposition methods, which are described in Deliverable 3.3.

Optimisations achieved through the inclusion of battery storage capacity in the VPP

The VPP optimisation trial work, described in this deliverable, has shown that the optimisation algorithm developed in edgeFLEX can be scaled up to cover about 200 power plants under management. This is mainly enabled by the inclusion of battery storage capacity in the VPP asset portfolio. Furthermore, the optimisation uses high-speed computing, which is key to increasing profits through arbitrage on the energy markets.

Without a battery, balancing wind farms only means costs, and the more balancing farms there are, the greater the costs of covering the deficit. On top of that, the greater the balancing burden, the lower the turnover of the power plants will be. But the battery makes it possible to use surplus energy and thus exceed *independent revenues*.

Including a biogas power plant in the VPP increases the width of the inverted U-curve (desirable), but decreases its altitude (undesirable), whereas including a battery increases both characteristics.

Economies-of-scale optimisation achieved through increasing the diversity of managed assets

In addition, the effect of economies of scale, in terms of portfolio setup and capacity, can clearly be seen in the results achieved, as larger and more diverse portfolios will generate more revenue per unit of power than smaller and less diverse asset portfolios. These economy of scale effects are not only enabled by more effective energy market trading but also by reducing the proportion made up by fixed costs of costs in the total costs of a VPP through the more efficient and effective management of the VPP assets. Fixed costs make up a quite high proportion of costs in VPP aggregation operations.

Investment opportunities and reductions of customer costs generated by the edgeFLEX optimisation

The increased return on investment achievable by an optimised VPP can be directed towards investments in the diversification and growth of the VPP portfolio, thus leading to further optimisation and synergies. Furthermore, the increased revenue generated can be distributed to the customer of the VPP aggregator through the reduction in service prices which the VPP aggregator can offer to its customers.

The need for new regulation to minimise unwanted imbalances in the grid

Because the sale of surplus energy generates income for the assets of a VPP, it is profitable for the asset owners to deliberately generate as much surplus energy as possible and it is acceptable to the asset owners that if the batteries cannot absorb the excess energy generated, as it can be sold on the ID market. To avoid this unscheduled overproduction of energy which causes problems to grid operators to balance the grid, new regulation is needed. For example, regulations should include a penalty in the objective function for increasing z_t^s variables. The earning of surplus energy should only be allowed after everything possible has been done to cover the imbalance created by the overproduction. That is why an operator whose goal is to regulate the system is needed e.g., by setting specific objective value coefficients in the optimisation, and whose remuneration is proportional to metrics of the minimisation of the imbalance.

Incentives for asset owners to join a VPP generated by the edgeFLEX VPP optimisation

In our edgeFLEX optimised VPP system, the maximum increase in income over *independent profits* is about 30 per cent. This surplus income can be used not only to allow assets to exceed their independent income, but also for investment. And when investing, insights from sensitivity analysis come into play. These investments are an additional catalyser of the growth of the VPP.

When the size of these virtual power plants exceeds a certain level, these results can be used to reform the grid.

8. List of Tables

9. List of Figures

10. References

[1] Omelčenko V., Manokhin V. (2021). Optimal Balancing of Wind farms with Virtual Power Plants. Frontiers in Energy Research. Doi: 10.3389/fenrg.2021.665295

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11. List of Abbreviations

4G	Fourth-generation wireless
5G	Fifth-generation wireless
ALPQ	Alpiq AG
API	Application programming interface
AWS	Amazon Web Services
CBC	Coin-or branch and cut
CO_2	Carbon dioxide
CPU	Central processing unit
DA	Day-ahead (market)
DER	Distributed energy resources
DT	Downtime; if a turbine is off, it must be off for DT units of time
DT	Default task
EPEX SPOT	European Power Exchange
HV	High voltage
ICT	Information and communications technology
ID	Intraday (market)
IP	Independent profits
kWh	Kilowatt-hour
LOB	Limit order book
LTE	Long term evolution
LSTM	Long short-term memory
MAE	Mean absolute error
MCP	Market clearing price
MPC	Model predictive control
MSE	Mean squared error
mSSA	Multichannel singular spectrum analysis
MV	Medium voltage
MWh	Megawatt-hour
PFC	Price forward curve

RAM	Random access memory
RES	Renewable energy sources
REST	Representational state transfer
SCADA	Supervisory control and data acquisition
TSO	Transmission system operator
UT	Uptime; if a turbine is on, it must be on for UT units of time
URL	Uniform resource locator
URLLC	Ultra Reliable Low Latency Communications
vCPU	Virtual central processing unit
VPP	Virtual power plant